Titre: Title:	Reliable, Context-Aware and Energy-Efficient Architecture for Wireless Body Area Networks in Sports Applications
Auteur: Author:	Richard Jaramillo Herrera
Date:	2016
Type:	Mémoire ou thèse / Dissertation or Thesis
Référence: Citation:	Jaramillo Herrera, R. (2016). Reliable, Context-Aware and Energy-Efficient Architecture for Wireless Body Area Networks in Sports Applications [Thèse de doctorat, École Polytechnique de Montréal]. PolyPublie. https://publications.polymtl.ca/2107/

URL de PolyPublie: PolyPublie URL:	https://publications.polymtl.ca/2107/
Directeurs de recherche: Advisors:	Alejandro Quintero, & Steven Chamberland
Programme: Program:	Génie informatique

UNIVERSITÉ DE MONTRÉAL

RELIABLE, CONTEXT-AWARE AND ENERGY-EFFICIENT ARCHITECTURE FOR WIRELESS BODY AREA NETWORKS IN SPORTS APPLICATIONS

RICHARD JARAMILLO HERRERA

DÉPARTEMENT DE GÉNIE INFORMATIQUE ET GÉNIE LOGICIEL

ÉCOLE POLYTECHNIQUE DE MONTRÉAL

THÈSE PRÉSENTÉE EN VUE DE L'OBTENTION

DU DIPLÔME DE PHILOSOPHIAE DOCTOR

(GÉNIE INFORMATIQUE)

AVRIL 2016

UNIVERSITÉ DE MONTRÉAL

ÉCOLE POLYTECHNIQUE DE MONTRÉAL

Cette thèse intitulée:

RELIABLE, CONTEXT-AWARE AND ENERGY-EFFICIENT ARCHITECTURE FOR WIRELESS BODY AREA NETWORKS IN SPORTS APPLICATIONS

présentée par : JARAMILLO HERRERA Richard

en vue de l'obtention du diplôme de : Philosophiae Doctor

a été dûment acceptée par le jury d'examen constitué de :

Mme BELLAÏCHE Martine, Ph.D., présidente

M. QUINTERO Alejandro, Doctorat, membre et directeur de recherche

M. CHAMBERLAND Steven, Ph.D., membre et codirecteur de recherche

M. PIERRE Samuel, Ph.D., membre

M. AJIB Wessam, Ph.D., membre externe

DEDICATION

To my children Lucas and Richard, my two miracles come true.

ACKNOWLEDGEMENTS

To God for guiding my way and taking my hand all the time.

To Professor Alejandro Quintero for the opportunity, his guidance and huge patience.

To Professor Steven Chamberland for his guidance and advice.

To my wife Shirley Carvajal for his love, his encouraging words and unconditional help.

To my friend Lina Maria Garcia for opening the way to this dream.

RÉSUMÉ

Un Réseau Corporel Sans Fil (RCSF, Wireless Body Area Network en anglais ou WBAN) permet de collecter de l'information à partir de capteurs corporels. Cette information est envoyée à un hub qui la transforme et qui peut aussi effectuer d'autres fonctions comme gérer des événements corporels, fusionner les données à partir des capteurs, percevoir d’autres paramètres, exécuter les fonctions d’une interface d’utilisateur, et faire un lien vers des infrastructures de plus haut niveau et d’autres parties prenantes.

La réduction de la consommation d'énergie d’un RCSF est un des aspects les plus importants qui doit être amélioré lors de sa conception. Cet aspect peut impliquer le développement de protocoles de Contrôles d'Accès au Support (CAS, Media Access Control en anglais ou MAC), protocoles de transport et de routage plus efficients. Le contrôle de la congestion est un autre des facteurs les plus importants dans la conception d’un RCSF, parce que la congestion influe directement sur la Qualité De Service (QDS, Quality of Service en anglais ou QoS) et l’efficience en énergie du réseau. La congestion dans un RCSF peut produire une grande perte de paquets et une haute consommation d’énergie. La QDS est directement impactée par la perte de paquets. L’implémentation de mesures additionnelles est nécessaire pour atténuer l’impact sur la communication des RCSF.

Les protocoles de CAS pour RCSF devraient permettre aux capteurs corporels d’accéder rapidement au canal de communication et d’envoyer les données au hub, surtout pour les événements urgents tout en réduisant la consommation d’énergie. Les protocoles de transport pour RCSF doivent fournir de la fiabilité bout-à-bout et de la QDS pour tout le réseau. Cette tâche peut être accomplie par la réduction du ratio de perte de paquets (Packet Loss Ratio en anglais ou PLR) et de la latence tout en gardant l'équité et la faible consommation d'énergie entre les nœuds.

Le standard IEEE 802.15.6 suggère un protocole de CAS qui est destiné à être applicable à tous les types de RCSF; toutefois, ce protocole peut être amélioré pour les RCSF utilisés dans le domaine du sport, où la gestion du trafic pourrait être différente d’autres réseaux. Le standard IEEE 802.15.6 comprend la QDS, mais cela ne suggère aucun protocole de transport ou système de contrôle du débit.

Le but principal de ce projet de recherche est de concevoir une architecture pour RCSF en trois phases : (i) Conception d'un mécanisme sensible au contexte et efficient en énergie pour fournir une QDS aux RCSF; (ii) Conception d'un mécanisme fiable et efficient en énergie pour fournir une récupération des paquets perdus et de l'équité dans les RCSF; et (iii) Conception d'un système de contrôle du débit sensible au contexte pour fournir un contrôle de congestion aux RCSF. Finalement, ce projet de recherche propose une architecture fiable, sensible au contexte et efficiente en énergie pour RCSF utilisés dans le domaine du sport. Cette architecture fait face à quatre défis : l'efficacité de l'énergie, la sensibilité au contexte, la qualité de service et la fiabilité.

La mise en place de cette solution aidera à l'amélioration des compétences, de la performance, de l'endurance et des protocoles d'entraînement des athlètes, ainsi qu'à la détection des points faibles. Cette solution pourrait être prolongée à l'amélioration de la qualité de vie des enfants, des personnes malades ou âgées, ou encore aux domaines militaires, de la sécurité et du divertissement.

L'évaluation des protocoles et schémas proposés a été faite par simulations programmées avec le simulateur OMNeT++ et le système Castalia. Premièrement, le protocole de CAS proposé a été comparé avec les protocoles de CAS suivants : IEEE 802.15.6, IEEE 802.15.4 et T-MAC (Timeout MAC). Deuxièmement, le protocole de CAS proposé a été comparé avec le standard IEEE 802.15.6 avec et sans l'utilisation du protocole de transport proposé. Finalement, le protocole de CAS proposé et le standard IEEE 802.15.6 ont été comparés avec et sans l'utilisation du système de contrôle du débit proposé.

Le protocole de CAS proposé surpasse les protocoles de CAS IEEE 802.15.6, IEEE 802.15.4 et T-MAC dans le pourcentage de pertes de paquets d'urgence et normaux, l'efficacité en énergie, et la latence du trafic d'urgence et du trafic normal. Le protocole de CAS proposé utilisé avec le protocole du transport proposé surpasse la performance du standard IEEE 802.15.6 dans le pourcentage de perte de paquets avec ou sans trafic d'urgence, l'efficacité en énergie, et la latence du trafic normal. Le système de contrôle du débit proposé a amélioré la performance du protocole de CAS proposé et du standard IEEE 802.15.6 dans le pourcentage de perte de paquets avec ou sans trafic d'urgence, l'efficacité en énergie, et la latence du trafic d'urgence.

ABSTRACT

Information collected from body sensors in a Wireless Body Area Network (WBAN) is sent to a hub or coordinator which processes the information and can also perform other functions such as managing body events, merging data from sensors, sensing other parameters, performing the functions of a user interface and bridging the WBAN to higher-level infrastructure and other stakeholders.

The reduction of the power consumption of a WBAN is one of the most important aspects to be improved when designing a WBAN. This challenge might imply the development of more efficient Medium Access Control (MAC), transport and routing protocols. Congestion control is another of the most important factors when a WBAN is designed, due to its direct impact in the Quality of Service (QoS) and the energy efficiency of the network. The presence of congestion in a WBAN can produce a big packet loss and high energy consumption. The QoS is also impacted directly by the packet loss. The implementation of additional measures is necessary to mitigate the impact on WBAN communications.

The MAC protocols for WBANs should allow body sensors to get quick access to the channel and send data to the hub, especially in emergency events while reducing the power consumption. The transport protocols for WBANs must provide end-to-end reliability and QoS for the whole network. This task can be accomplished through the reduction of both the Packet Loss Ratio (PLR) and the latency while keeping fairness and low power consumption between nodes.

The IEEE 802.15.6 standard suggests a MAC protocol which is intended to be applicable for all kinds of WBANs. Nonetheless, it could be improved for sports WBANs where the traffic-types handling could be different from other networks. The IEEE 802.15.6 standard supports QoS, but it does not suggest any transport protocol or rate control scheme.

The main objective of this research project is to design an architecture for WBANs in three phases: (i) Designing a context-aware and energy-efficient mechanism for providing QoS in WBANs; (ii) Designing a reliable and energy-efficient mechanism to provide packet loss recovery and fairness in WBANs; and (iii) Designing a context-aware rate control scheme to provide congestion control in WBANs. Finally, this research project proposes a reliable, context-

aware and energy-efficient architecture for WBANs used in sports applications, facing four challenges: energy efficiency, context awareness, quality of service and reliability.

The benefits of this solution will help to improve skills, performance, endurance and training protocols of athletes, and deficiency detection. Also, it could be extended to enhance the quality of life of children, ill and elderly people, and to security, military and entertainment fields.

The evaluation of the proposed protocols and schemes was made through simulations programed in the OMNeT++ simulator and the Castalia framework. First, the proposed MAC protocol was compared against the IEEE 802.15.6 MAC protocol, the IEEE 802.15.4 MAC protocol and the T-MAC (Timeout MAC) protocol. Second, the proposed MAC protocol was compared with the IEEE 802.15.6 standard with and without the use of the proposed transport protocol. Finally, both the proposed MAC protocol and the IEEE 802.15.6 standard were compared with and without the use of the proposed rate control scheme.

The proposed MAC protocol outperforms the IEEE 802.15.6 MAC protocol, the IEEE 802.15.4 MAC protocol and the T-MAC protocol in the percentage of emergency and normal packet loss, the energy effectiveness, and the latency of emergency and normal traffic. The proposed MAC protocol working along with the proposed transport protocol outperforms the IEEE 802.15.6 standard in the percentage of the packet loss with or without emergency traffic, the energy effectiveness, and the latency of normal traffic. The proposed rate control scheme improved the performance of both the proposed MAC protocol and the IEEE 802.15.6 standard in the percentage of the packet loss with or without emergency traffic, the energy effectiveness and the latency of emergency traffic.

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LIST OF SYMBOLS AND ABBREVIATIONS

3RP	Reallocation, Retransmission and Rate-control Phase
Ack	Acknowledgement
ADC	Analog-to-Digital Converter
ARC	Adaptive Rate Control
B-Ack	Block Acknowledgment
BAN	Body Area Network
BANMAC	Body Area Network MAC
BASN	Body Area Sensor Network
BCC	Body-Coupled Communication
BSN	Body Sensor Network
BER	Bit Error Rate
BLE	Bluetooth Low Energy
BM	Battery Module
CAP	Contention Access Phase
CA-MAC	Context-Aware MAC
CCF	Congestion Control and Fairness
CFT	Continuous Frame Transmission
CICADA	Cascading Information by Controlling Access with Distributed slot Assignment
CODA	Congestion Detection and Avoidance
CRC	Cycling Redundancy Check
CS	Contention Slot
CSMA/CA	Carrier Sense Multiple Access/Collision Avoidance
CW	Contention Window

DQBAN	Distributed Queuing Body Area Network
DTDMA	Dynamic-TDMA
EAP	Exclusive Access Phase
ECG	Electrocardiograms
ECODA	Enhanced Congestion Detection and Avoidance
EECC	Energy Efficient Congestion Control
EEG	Electroencephalograph
EMG	Electromyograph
ESRT	Event-to-Sink Reliable Transport
FCC	Federal Communication Commission
FDMA	Frequency Division Multiple Access
GRDT	Group-based Reliable Data Transport
GTS	Guaranteed Time Slot
H-MAC	Heartbeat-MAC
HBC	Human Body Communication
IBC	Intra-Body Communication
I-Ack	Immediate Acknowledgment
IMD	Implantable Medical Device
IRCRT	Improved Rate-Controlled Reliable Transport
ISM	Industrial, Scientific Medical
L-Ack	Later Block Acknowledgment
MAC	Medium Access Control
MAP	Managed Access Phase
MEP	Management and Emergency Phase

MICS	Medical Implant Communications Service
MM	Memory Module
N-Ack	Non-Acknowledgment
NACK	Negative Acknowledgement
NB	Narrow Band
PAN	Personal Area Network
PCC	Priority-based Coverage-aware Congestion
PCCP	Priority-based Congestion Control Protocol
PDR	Packet Delivery Ratio
PLR	Packet Loss Ratio
PM	Processing Module
PRA	Priority-base rate Adjustment Algorithm
PSFQ	Pump Slowly Fetch Quickly
pSIFS	Priority Short Inter-Frame Space
QoS	Quality of Service
QSPS	Quasi-Sleep-Preempt-Supported
RAP	Random Access Phase
RCF	Rate Control Factor
RCS	Rate Control Scheme
RF	Radio Frequency
RFID	Radio Frequency Identification Devices
RFM	Radio Frequency Module
RIB	Reallocation/Retransmission/Rate-control Indicator Bit
RMST	Reliable Multi-Segment Transport

RTS	Request to Send
SCAP	Special Contention Access Phase
SM	Sensing Module
SMF	Slot Multiplication Factor
SMP	Sensor Management Protocol
SNR	Signal to Noise Ratio
SRP	Slot Reallocation Phase
S-MAC	Synchronous-MAC
TAD-MAC	Traffic-Aware Dynamic MAC
TCP	Transmission Control Protocol
TDMA	Time Division Multiple Access
T-MAC	Timeout-MAC
UDP	User Datagram Protocol
UHCC	Upstream Hop-by-Hop Congestion
UWB	Ultra-Wideband
WAN	Wide Area Network
WBAN	Wireless Body Area Network
WBSN	Wireless Body Sensor Network
WLAN	Wireless Local Area Network
WMAN	Wireless Metropolitan Area Network
WMTS	Wireless Medical Telemetry Service
WPAN	Wireless Personal Area Network
WSN	Wireless Sensor Network

CHAPTER 1 INTRODUCTION

Wireless Body Area Networks (WBANs) allow gathering data from sensors interconnected on, near, or within the human body. They are also known as Wireless Body Sensor Networks (WBSNs), Body Area Sensor Networks (BASNs), Body Sensor Networks (BSNs) or Body Area Networks (BANs). In this document, they will be called WBANs. The body sensors (also known as nodes) provide data to a hub (also known as sink, coordinator or body aggregator), which is central to managing body events and perform a multitude of functions like additional sensing, node registration, initialization, customization, secure communication, fusing data from sensors across the body, serving as a user interface and bridging the WBAN to higher-level infrastructure and thus to other stakeholders.

The IEEE 802.15.6 Standard ("IEEE Standard for Local and metropolitan area networks - Part 15.6: Wireless Body Area Networks," 2012) categorizes WBAN applications into medical and non-medical. Furthermore, some authors have created some subcategories for these two classifications. Medical applications of WBANs have been classified into three subcategories: (i) Wearable WBAN (e.g. Assessing Soldier Fatigue and Battle Readiness, Sleep Staging, Asthma and Wearable Health Monitoring, Physical Rehabilitation); (ii) Implant WBAN (e.g. Diabetes Control, Cardiovascular Diseases and Cancer Detection); (iii) Remote Control of Medical Devices (e.g. Patient Monitoring and Telemedicine Systems). Non-medical applications of WBANs have been classified into five subcategories: Real Time Streaming, Entertainment Applications (Activity Recognition and Gait Analysis), Emergency (non-medical), Emotion Detection (Emotional Stress Detection) and Secure Authentication (Handshake Detection) (Fortino, Giannantonio, Gravina, Kuryloski, & Jafari, 2013; Movassaghi, Abolhasan, Lipman, Smith, & Jamalipour, 2014). Other authors have made the classification in three main categories: Healthcare, Sports and Entertainment, and Military and Defense (Cavallari, Martelli, Rosini, Buratti, & Verdone, 2014).

The sensor nodes and the hubs use a communication protocol stack which consists of five layers: (i) Physical layer – responsible for frequency selection, carrier frequency generation, signal detection, modulation, and data encryption; (ii) Data link layer – responsible for the multiplexing of data streams, data frame detection, medium access and error control; (iii) Network layer – responsible of providing special multihop wireless routing protocols between the sensor nodes and the hub; (iv) Transport layer – especially needed when the system is planned to be accessed through the Internet or other external networks; and (v) Application layer – that includes the application running on the node which may be specific to the sensor type as well as management, security, synchronization, and query type functions. The communication protocol stack also suggests three additional planes for each sensor and the hub: power management plane (how the sensor node uses its power), mobility management plane (detecting and registering the movement of the sensor nodes) and task management plane (balancing and scheduling the sensing tasks given to a specific region) (Akyildiz, Weilian, Sankarasubramaniam, & Cayirci, 2002).

There are many challenges for the design of WBANs like: the energy efficiency that may require new MAC (Media Access Control) protocols, new routing protocols and new energy scavenging sources; the impact of data loss that may require additional measures in order to ensure the Quality of Service (QoS); the reliability to grant accuracy and guarantee on-time delivery of data; the higher security level in order to protect personal information; the coexistence and interference of several WBANs; the nodes wearability (small size, light weight, low complexity, reconfigurability and biocompatibility); the context awareness for responding according to the current situation in the network; the nodes and technologies heterogeneity; the variable network topology support due to body movement; and the nodes placement optimization. Hanson et al. (2009) mention the critical need for collaboration between technologists and domain experts who can help to define the specifications and requirements for WBAN systems and applications.

OMNeT++ simulation framework and Castalia simulator were used for the simulations of the proposed solutions. OMNeT++ is an extensible, modular, component-based C++ simulation library and framework, primarily for building network simulators (Varga, 2001). Castalia is a simulator based on the OMNeT++ platform, for WSN, WBAN and generally networks of low-power embedded devices (NICTA, 2013). Castalia v3.2 is distributed with a MAC model implementation of the IEEE 802.15.6 MAC protocol, called BaselineBAN. This implementation was used for the comparisons with the proposed solutions.

1.1 Basic Concepts

1.1.1 Wireless Body Area Networks

Wireless Body Area Networks (WBANs) allow gathering data from sensors interconnected on, near, or within the human body. The body sensors provide data to a hub (also known as sink, coordinator or body aggregator), which is central to managing body events and perform a multitude of functions like sensing, fusing data from sensors across the body, serving as a user interface and bridging the WBAN to higher-level infrastructures and thus to other stakeholders.

The general architecture of a WBAN is presented by Lai et al. (2013) and is depicted in the Figure 1.1. The sensor nodes which are placed in/on the human body collect physical data and perform preliminary processing. The data are gathered by a sink node (hub) and then transmitted to a base station in order to be shared over the Internet.

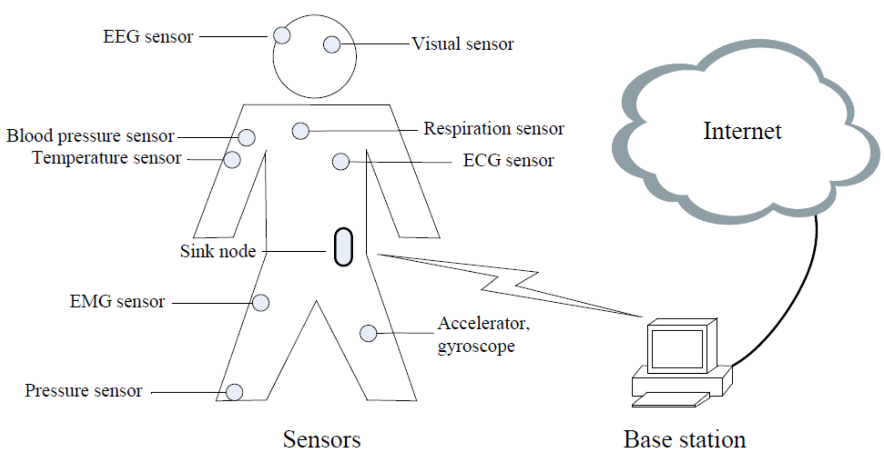

Figure 1.1. WBAN - General Architecture

Alemdar and Ersoy (2010) have given an overview of a simple wireless sensor network application scenario for healthcare that is depicted in the Figure 1.2. There are four different categories of actors other than the power users of the systems such as administrators and developers. They are: children, elderly and chronically ill, caregivers and healthcare professionals. There are five subsystems in such a scenario: (i) Body Area Network Subsystem – the Ad Hoc sensor network and tags that the children and the elderly carry on their body; (ii) Personal Area Network Subsystem – composed of environmental sensors deployed around and mobile or nomadic devices that belong to the patient; (iii) Gateway to the Wide Area Networks –

a responsible from connecting the BAN and PAN (Personal Area Network) subsystems to the WANs (Wide Area Networks); (iv) Wide Area Networks (WANs) – used for a remote monitoring and tracking scenario. The gateway can relay information to one or more network systems depending on the application; and (v) End-user healthcare monitoring application – where the collected data is interpreted and required actions are triggered. The application has a processing part and a graphical user interface part.

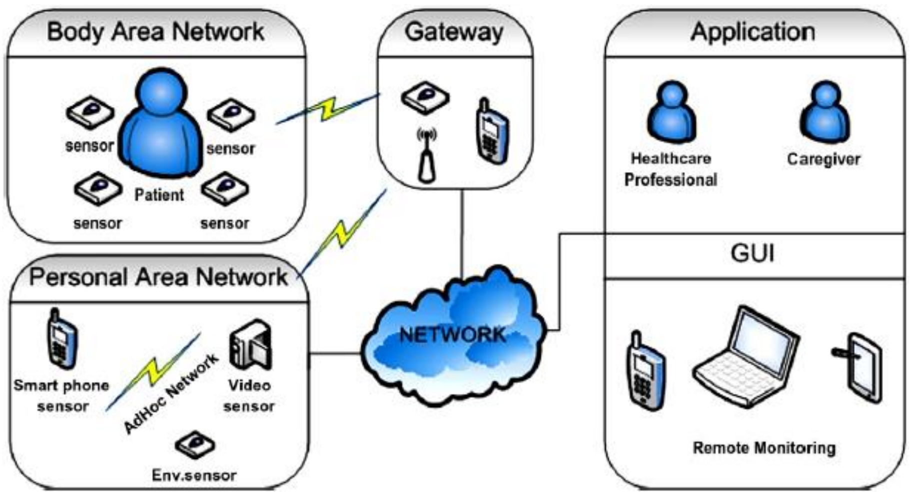

Figure 1.2. Overview of a simple WSN application scenario for healthcare

N. A. Khan et al. (2012) have mentioned some tasks for the hub (or personal server as they called it): node registration (e.g., type and number of sensors), initialization (e.g., state sampling frequency and operation mode), customization (e.g., run user-specific adjustment), secure communication (key exchange), time synchronization, channel sharing, data recovery, data processing, coalition of the data, and authentication information. The hub must function in such a manner that the data is transmitted when the link with the Internet is available. However, when the link is not available, the hub stores the data locally and transmits it after the availability of the communication channel or link.

Alemdar and Ersoy (2010) have enumerated some design considerations for each pervasive healthcare monitoring subsystem:

- Body Area Network Subsystem: power consumption, transmission power, unobtrusiveness, portability, real-time availability, reliable communications, multi-hop routing and security.

- Personal Area Network Subsystem: energy efficiency, scalability and self-organization between the nodes.
- Gateway to the Wide Area Networks: security and congestion prevention.
- Wide Area Networks: data rate, reliable communication protocols, secure data transmission and coverage.
- End-user healthcare monitoring application: privacy, security, reliability, user-friendliness, middleware design, scalability, interoperability and context awareness.

J. Y. Khan, Yuce, Bulger, and Harding (2010) present a WBAN architecture used in health monitoring which consists of three tiers: (i) The WBAN is the most predominant part of telemedical system and comprises of many intelligent nodes; (ii) Personal Server (PS) takes the information from sensor nodes about health status and transfer it to Medical Server through WLAN or any internet service. Its tasks are node registration (e.g., type and number of sensors), initialization (e.g., state sampling frequency and operation mode), customization (e.g., run user specific adjustment), and setup of a secure communication (key exchange). On successful configuration of WBAN, network is handled by PS, which also ensures time synchronization, channel sharing, data recovery, data processing, and coalition of the data. PS is also responsible for patient's authentication information; (iii) Medical Server (MS) is optimally used for provision of services to a large number of individual users. This tier also provides service to a complex network comprising of interconnected services, medical personnel and healthcare professionals.

The positioning of WBANs into the realm of wireless networks is depicted in the Figure 1.3. A WBAN is operated close to the human body and its communication range will be restricted to a few meters, with typical values around 1–2m. It is devoted to interconnection of one person's wearable devices; a WPAN is a network in the environment around the person with the communication range reaching up to 10 m for high data rate applications and up to several dozens of meters for low data rate applications; and a WLAN has a typical communication range up to hundreds of meters. Each type of network has its typical enabling technology: IEEE 802.15.1 (Bluetooth) or IEEE 802.15.4 (ZigBee) for a WPAN; IEEE 802.11 (WiFi) for a WLAN; and IEEE 802.16 (WiMax) for a WMAN. Finally, the communication in a WAN can be established via satellite links (Latré, Braem, Moerman, Blondia, & Demeester, 2011).

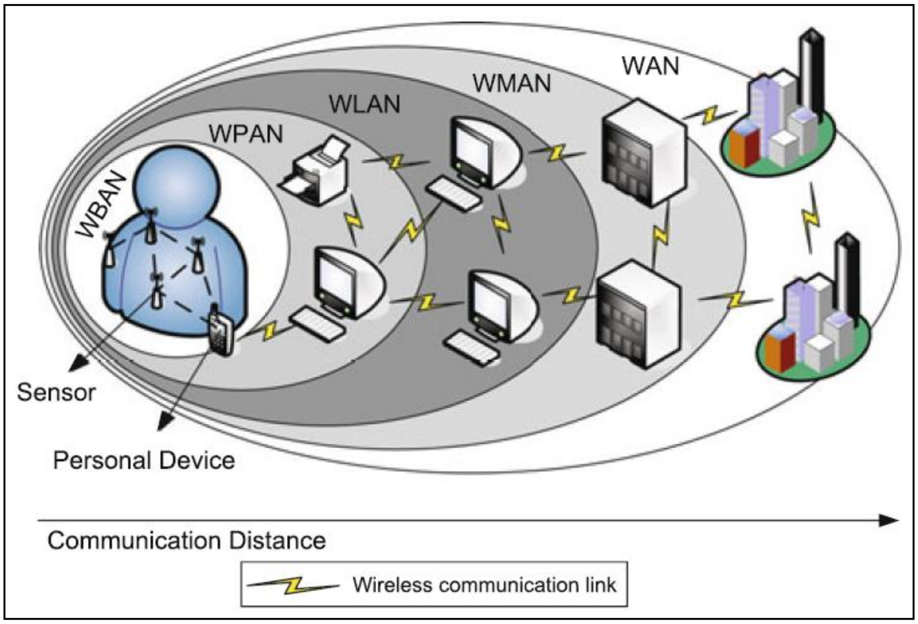

Figure 1.3. WBAN - Positioning in the realm of wireless networks

1.1.2 Sensors

Chen, Gonzalez, Vasilakos, Cao, and Leung (2010) show the general architecture for a typical sensor node and it is depicted in the Figure 1.4. The sensor node is composed of four modules: Microprocessor Module, Radio-Frequency Module, Sensor Module and Memory Module. The sensor module consists of a sensor, a filter and an Analog-to-Digital Converter (ADC). The sensor converts some form of energy to analog electric signals, which are bandpass-filtered and digitized by the ADC for further processing.

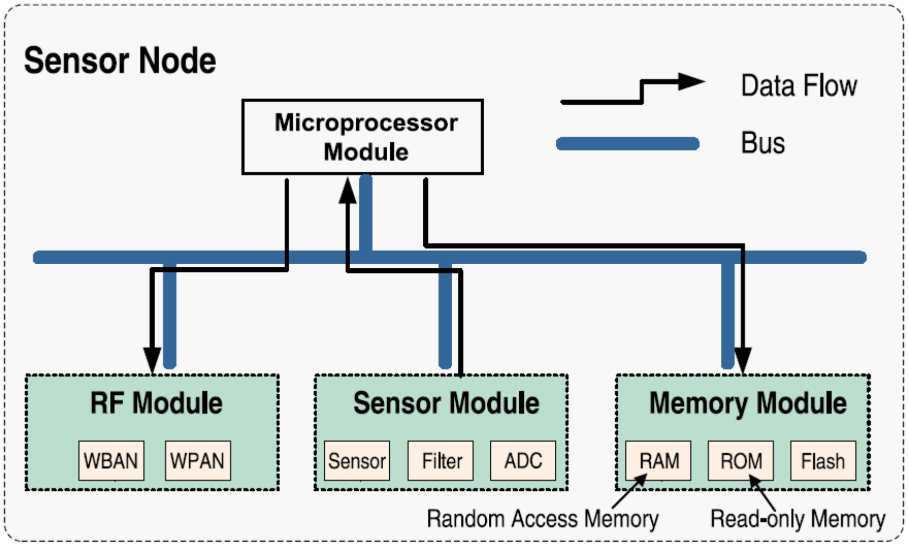

Figure 1.4. Sensor Node Architecture

Most Used Sensors

Lai et al. (2013) present some of the most used sensors in WBANs and they are listed in the Table 1.1. The table shows for each sensor its function, the signal type (continuous or discrete), the sampling frequency (high, low or very low) and the placement type (wearable, implantable or surrounding).

Table 1.1. Most used sensors in WBANs

Sensors	Function	Signal Type	Sampling Frequency	Placement
Accelerometer	Obtaining acceleration on each spatial axis of three-dimensional space.	Continuous	High	Wearable
Artificial cochlea	Converting voice signal into electric pulse and sending it to implanted electrodes in ears, generating auditory sensation by stimulating acoustic nerves.	Continuous	High	Implantable
Artificial retina	Receiving pictures captured by external camera and converting them to electric pulse signals, which are used to stimulate optic nerves to generate visual sensations.	Continuous	High	Implantable
Blood-pressure sensor	Measuring the peak pressure of systolic and the minimum	Discrete	Low	Wearable

Sensors	Function	Signal Type	Sampling Frequency	Placement
	pressure of diastolic.			
Camera pill	Detecting gastrointestinal tract by wireless endoscope technique.	Continuous	High	Implantable
Carbon dioxide sensor	Measuring the content of carbon dioxide from mixed gas by infrared technique.	Discrete	Low/Very low	Wearable
ECG/EEG/EMG sensor	Measuring voltage difference between two electrodes which are placed on surface of body.	Continuous	High	Wearable
Gyroscope	Measuring angular velocity of rotating object according to principle of angular momentum conservation.	Continuous	High	Wearable
Humidity sensor	Measuring humidity according to the changes of resistivity and capacitance caused by humidity changes.	Discrete	Very low	Wearable
Blood oxygen saturation sensor	Measuring blood oxygen saturation by absorption ratio of red and infrared light passing through a thin part of body.	Discrete	Low	Wearable
Pressure sensor	Measuring pressure value according to the piezoelectric effect of dielectric medium.	Continuous	High	Wearable/ Surrounding
Respiration sensor	Obtaining respiration parameters indirectly by detecting the expansion and contraction of chest or abdomen.	Continuous	High	Wearable
Temperature sensor	Measuring temperature according to the changes of materials physical properties.	Discrete	Very low	Wearable
Visual sensor	Capturing features of subject, including length, count, location, and area.	Continuous/ Discrete	High/Low	Wearable/ Surrounding

There are other wearable devices like glucose sensors, fall detection sensors, emergency call devices; and other implantable devices like pacemakers, cardioverter-defibrillator, intracranial pressure sensors and insulin pumps (Timmons & Scanlon, 2009).

Devices Classification

According to Lai et al. (2013), sensors can be classified by the type of data transmission media, the type of measured signals, the deployment position, and their automatic adjustment ability.

Considering the type of data transmission media, sensors can be divided in:

- Wireless Sensors: this type of sensor uses wireless communication technologies such as Bluetooth or Zigbee, Radio Frequency Identification Devices (RFID), and Ultra-Wideband (UWB) to communicate with other sensors or devices.
- Wired Sensors: this type of sensor uses wired communication technologies and can replace wireless sensors if wearability is not seriously affected. The transmission mode is more stable than that of wireless sensors, but their installation and deployment is relatively complicated.
- Human Body Communication (HBC) Sensors: HBC or Intra-Body Communication (IBC) is a novel non-RF (Radio Frequency) wireless data communication technique which uses the human body itself as transmission medium for electrical signals (Seyedi, Kibret, Lai, & Faulkner, 2013). They use sub-GHz frequencies without antennae, which reduce the power consumption and the size of sensor nodes, so, they can easily be integrated into body-worn devices. Typically a wireless biomedical device consists of two parts: the external part that transmits RF signals to the internal part through an inductive coupling downlink using variety of modulated signals such as Amplitude Shift Keying (ASK), Frequency Shift Keying (FSK), Phase Shift Keying (PSK), and it must transmit with high efficiency and low power consumption (Hannan, Abbas, Samad, & Hussain, 2011).

Considering the type of measured signals, sensors can be divided in:

- Continuous Time-varying Signals: this type of sensor uses very large data transmission quantity and very large power consumption because of the real-time signal acquisition. Some examples are: ECG (Electrocardiogram) sensor, EEG (Electroencephalograph) sensor, EMG (Electromyograph) sensor, accelerometers, gyroscopes, visual sensor and auditory sensor.

- Discrete Time-varying Signals: this type of sensor uses smaller data transmission quantity because of the slowly changing of signals that sensors collect. Some examples are: glucose sensor, temperature sensor, humidity sensor, blood pressure monitor and pulse oximeter.

Considering the deployment position, sensors can be divided in:

- Wearable Sensors: the size and weight of this type of sensor should be considered in the design process, in order not to interfere with the usual activity of users. Some examples are: temperature sensor, pressure sensor and accelerometer.
- Implantable Sensors: this type of sensor can be implanted or ingested into the body, and therefore they need to be tiny enough, non-corrosive and biocompatible. Some examples are: pacemaker, cochlear implant and camera pill.
- Placed-surrounding-people Sensors: this type of sensor can be placed surrounding people and can be used to recognize behaviors and collect information about the environment. One example is the visual sensors.

Considering the automatic adjustment ability, sensors can be divided in:

- Self-adapting sensors: this type of sensors can automatically adjust processing method, order and parameters, boundary conditions or constraints according to data characteristics, make themselves adapt to the statistical distribution and structural characteristics of the measured data, in order to get the best treatment effect.
- Non-self-adapting sensors: this type of sensors is simple to design and needs no consideration of self-adjusting function.

According to Hanson et al. (2009), sensors can be divided in three additional categories:

- Physiological sensors, that measure ambulatory blood pressure, continuous glucose monitoring, core body temperature, blood oxygen, and signals related to respiratory inductive plethysmography, ECG, EEG, and EMG.
- Bio-kinetic sensors, that measure acceleration and angular rate of rotation derived from human movement.
- Ambient sensors, that measure environmental phenomena, such as humidity, light, sound, pressure level and temperature.

1.1.3 Communication Technologies

Bluetooth

Bluetooth technology was designed as a short range wireless communication standard, and later widely used for connecting a variety of personally carried devices to support data and voice applications. As a WPAN technology, two or more (up to eight) Bluetooth devices form a short-range network called Piconet, where devices are synchronized to a common clock and hopping sequence at the same physical channel. Bluetooth devices operate in the 2.4 GHz ISM (Industrial Scientific Medical) band, utilizing frequency hopping among 79 1 MHz channels at a nominal rate of 1,600 hops/sec to reduce interference (Chen et al., 2010).

Bluetooth Low Energy

Bluetooth Low Energy technology, formerly known as Bluetooth Low End Extension (BLE), and later Wibree, provides ultra-low power consumption and cost. It was designed to wirelessly connect small devices to mobile terminals. Its major difference from Bluetooth resides in the radio transceiver, baseband digital signal processing and data packet format. Using fewer channels for pairing devices, synchronization can be done in a few milliseconds compared to Bluetooth's seconds. It can be categorized into two groups: dual-mode chips and stand-alone chips. Stand-alone chips are intended to be equipped with sensors/actuators and to communicate with other standalone or dual-mode chips, while dual-mode chips are also able to connect to conventional Bluetooth devices.

Compared to its counterpart Zigbee technology, Bluetooth Low Energy technology has less communication overhead because it is devised for inter-WBAN communication exclusively by supporting a single hop topology, short range coverage, and compatibility with widely used Bluetooth devices (Chen et al., 2010). However, Hughes, Wang, and Chen (2012) pose that although the likely wide adoption of BLE as a low power WSN standard cannot be ignored, the standard does not support QoS and is not specifically designed for WBAN applications.

Zigbee/IEEE 802.15.4

ZigBee/IEEE 802.15.4 targets low-data-rate and low-power-consumption applications. Chen et al. (2010) mention some reasons why Zigbee has become popular for communications between sensors:

- It incurs low energy consumption for communications between the nodes.
- It has a low duty cycle that enables it to provide longer battery life for the node.
- Its communication primitives enable low-latency communications.
- It supports 128-bit security.

Chen et al. (2010) identify the MAC layer responsibilities of IEEE 802.15.4: generating network beacons, synchronizing to network beacons, supporting MAC association and disassociation, supporting MAC encryption, employing unslotted/slotted CSMA/CA (Carrier Sense Multiple Access/Collision Avoidance) mechanism for channel access, and handling guaranteed time slot (GTS) allocation and management. The authors also mention some concerns about Zigbee: WBANs operate at 2.4 GHz and suffer from significant and highly variable path loss near the human body causing Zigbee to yield unsatisfactory performance; the maximum supported data rate is only 250 kbps which is inadequate to support real-time and large-scale WBANs; and there are other issues such as power, data rate, and frequency. ZigBee Health Care public application profile provides a flexible framework to meet Continua Health Alliance requirements for remote health and fitness monitoring. ZigBee may have a better chance to be adopted in the area of home automation and industrial automation and control. Hughes et al. (2012) pose that although 802.15.4 has been proven as a suitable standard for multi-hop WSNs providing QoS and adequate data rates, it is not the best solution for low power communications in WBANs.

Other Technologies

Chen et al. (2010) and Patel and Jianfeng (2010) mention some other communication technologies:

- ANT is a proprietary sensor network technology with the features of a light-weight protocol stack, ultra-low power consumption, and a data rate of 1 Mbps. ANT works in the 2.4 GHz ISM band and employs the TDMA (Time Division Multiple Access) access method.
- RuBee is a two-way, active wireless protocol that uses long wave magnetic signals to send and receive short (128 byte) data packets in a local network.
- Sensium provides a proprietary ultra-low-power platform for low data rate on-body applications. Using single-hop communication and centrally controlled sleep/wakeup

times leads to significant energy savings. It is featured as an ultra-low-power (3mA@1.2V) solution.

- Zarlink uses a Reed-Solomon coding scheme together with CRC (Cyclic Redundancy Check) error detection to achieve an extremely reliable link, as supported by a proprietary ultra-low power RF transmitter chip as an Implantable Medical Device (IMD). Zarlink's RF chip has been used in the world's first swallowable camera capsule.

1.1.4 IEEE 802.15.6 Standard

The IEEE 802.15.6 Standard specifies short-range, wireless communications in the vicinity of, or inside, a human body (but not limited to humans). It uses existing ISM bands as well as frequency bands approved by national medical and/or regulatory authorities. It allows devices to operate on very low transmit power for safety to minimize the specific absorption rate (SAR) into the body and increase the battery life ("IEEE Standard for Local and metropolitan area networks - Part 15.6: Wireless Body Area Networks," 2012).

The Figure 1.5 shows the network star topology suggested by the IEEE 802.15.6 Standard.

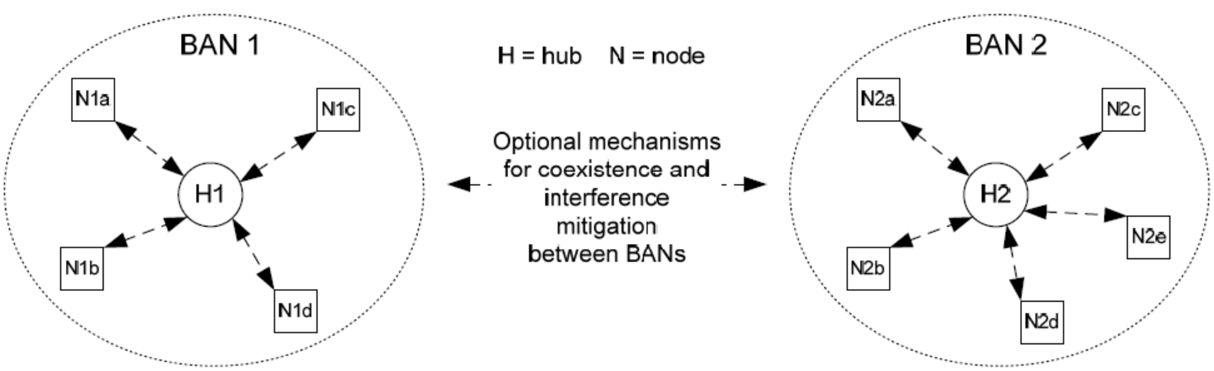

Figure 1.5. Network topology in IEEE 802.15.6

All nodes and the hub are internally partitioned into a physical (PHY) layer and a medium access control (MAC) sublayer, in accordance with the IEEE 802® reference model. The Figure 1.6 depicts the reference model for the IEEE 802.15.6 Standard.

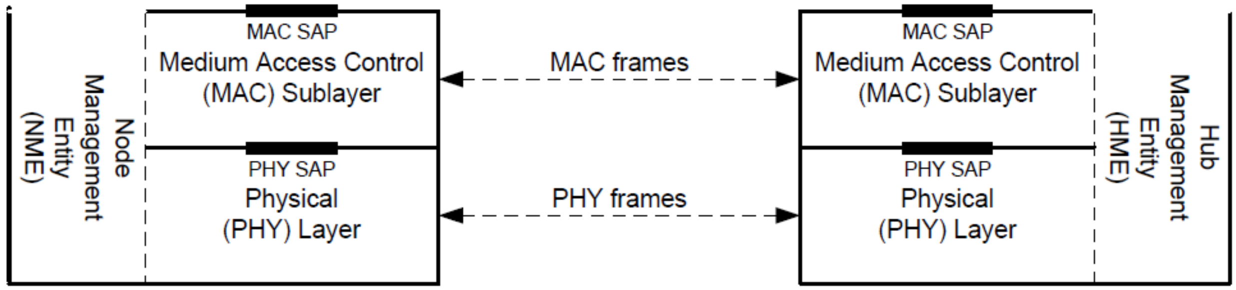

Figure 1.6. Reference model in IEEE 802.15.6 Standard

The IEEE 802.15.6 Standard divides the channel into beacon periods or superframes of equal length. Each beacon period contains a number of allocation slots used for data transmission. The hub transmits beacons to define the beacon period boundaries and the slot allocations. Generally, the hub transmits beacons in each beacon period except those that are inactive (Ullah, Mohaisen, & Alnuem, 2013). The Figure 1.7 depicts the time reference base proposed by the IEEE 802.15.6 Standard.

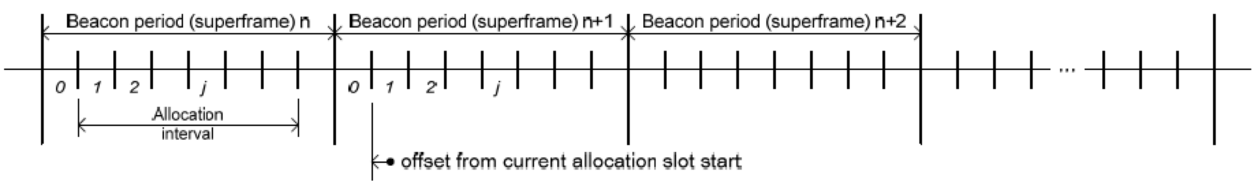

Figure 1.7. Time reference base in IEEE 802.15.6

The IEEE 802.15.6 Standard provides three access mechanisms for a beacon period: Random access, Improvised access and Scheduled access. (i) Random Access Mechanism – the hub may employ either a slotted ALOHA or CSMA/CA protocol, depending on the PHY. The hub considers slotted ALOHA and CSMA/CA protocols for Ultra-Wideband (UWB) and Narrow Band (NB), respectively; (ii) Improvised and Unscheduled Access Mechanism – the hub may use improvised access to send poll or post commands without pre-reservation or advance notice in beacon mode or non-beacon mode with superframe boundaries. These commands are used to initiate the transactions of one or more data frames by the nodes or hub outside the scheduled allocation interval; (iii) Scheduled and Scheduled-Polling Access Mechanisms – used to obtain scheduled uplink, downlink, and bilink allocations. In addition, the scheduled polling is used for polled and posted allocations ("IEEE Standard for Local and metropolitan area networks - Part 15.6: Wireless Body Area Networks," 2012).

The Table 1.2 shows the user priority mapping proposed by the IEEE 802.15.6 Standard to prioritize the medium access of the MAC frames.

Table 1.2. User priority mapping in IEEE 802.15.6

User priority	Traffic designation	Frame type
0	Background (BK)	Data
1	Best effort (BE)	Data
2	Excellent effort (EE)	Data
3	Video (VI)	Data
4	Voice (VO)	Data
5	Medical data or network control	Data or management
6	High-priority medical data or network control	Data or management
7	Emergency or medical implant event report	Data

1.2 Problem Statement

Current Personal Area Networks (PANs) do not meet the medical (proximity to human tissue) and relevant communication regulations for some application environments. Besides, they do not support the combination of reliability, QoS, low power, data rate, and non-interference required to broadly address the breadth of WBAN applications ("IEEE Standard for Local and metropolitan area networks - Part 15.6: Wireless Body Area Networks," 2012).

Lai et al. (2013) have mentioned that minimizing the power consumption as well as ensuring the quality of communication links is a long-term objective, and energy-efficient MAC and routing protocols remain to be developed. The authors also mention IEEE 802.15.6 has defined many WBAN band standards, so developing many upper layer protocols which support a variety of physical layer channel is an inevitable trend. Therefore, large amounts of work need to be done to balance the relationship between the computational cost and the accuracy of a system.

Hanson et al. (2009) have mentioned WBANs must effectively transmit and transform sensed phenomena into valuable information and do so while meeting other system requirements, such as energy efficiency. Marinkovic, Popovici, Spagnol, Faul, and Marnane (2009) suggests that it is useful to have gateway points in the network, such as nodes carried around the belt, which are less power constrained and can be used for network coordination.

Chen et al. (2010) have mentioned the battery-operated and low bit-rate features of existing body sensor devices make it a challenging issue to design an energy-efficient MAC protocol providing QoS. The authors also mention there is a trade-off into the MAC layer, between reliability, latency and energy consumption that needs to be resolved. Low duty cycle leads to lower throughput and higher packet delay. Adaptive adjustment of duty cycles is thus desirable for better performance. How to design a service differentiation and scheduling strategy that meets the real-time demands of certain sensors, while taking advantage of such broad sensor heterogeneity is also a significant challenge.

Ullah et al. (2009) have mentioned design and implementation of a new TDMA protocol is required which can accommodate the heterogeneous WBAN traffic in a power-efficient manner. The authors also mention MAC transparency has been a hot topic for the MAC designers since different bands have different characteristics in terms of the data rate, the number of sub-channels in a particular frequency band/channel, and the data prioritization. Therefore, a good MAC protocol for a WBAN should enable reliable operation on MICS, ISM, and UWB bands simultaneously. Hayat et al. (2012) have mentioned that TDMA is the most suitable scheduling scheme, even though it requires extra power consumption due to its sensitivity for synchronization.

Patel and Jianfeng (2010) have mentioned harmonized coexistence of multiple collocated WBANs in crowded places such as hospital elevators and wards needs a robust MAC protocol. Efficient duty cycling methods have to be developed to minimize power consumption without compromising QoS. Furthermore, the MAC protocol should be able to cope with topology and density changes induced by nodes moving in and out of range due to body movements. Marinkovic et al. (2009) suggest that if several networks should coexist in close vicinity, they should use different frequency channels.

Latré et al. (2011) have mentioned some nodes equipped with both RF and BCC (Body-Coupled Communication) capabilities. As a BCC is restricted to a person’s body, the BCC can be used to discover and identify sensor nodes on the same body and for waking up RF radios from low-power sleep mode. The authors also mention that several QoS solutions specific for WSNs have been proposed, but these solutions mainly focus on one or a few QoS features such as reliability, delay, bandwidth specification or reservation. It is important to achieve the right balance between power consumption and the desired reliability of the system.

Alemdar and Ersoy (2010) have mentioned a middleware helps to manage the inherent complexity and heterogeneity of medical sensor networks, isolating common behavior that can be reused by several applications and to encapsulate it as system services. In this way, multiple sensors and applications can be supported easily and resource management and plug and play function becomes easy.

J. Y. Khan et al. (2010) pose that into a WBAN it is advised to reduce the number of transmitted packets from sensor nodes reducing the contention level and power consumption of nodes in the network and improving reliability and delay performance. To achieve these objectives, the sensor nodes may aggregate multiple physiological data and transmit in a single packet.

WBANs need higher security level in order to protect personal information. Multimodal authentication schemes based on human faces, hand features, and EEG signals, are being actively developed in both academia and industry (Chen et al., 2010). Misuse or privacy concerns may restrict people from taking advantage of the full benefits from a WBAN. Even if the network is unattended for a longer time, security measures should always be in the highest priority mode (Al Ameen, Liu, & Kwak, 2012). The implementation of data security and privacy mechanisms carries some trade-offs to be considered like: conflicts between security and efficiency, between security and safety, and between security and usability (Li, Wenjing, & Kui, 2010). Gope and Hwang (2016) have enumerated the main security issues for WBANs used in healthcare: data privacy, data integrity, data freshness, authentication, anonymity, and secure localization.

Caldeira, Rodrigues, and Lorenz (2013) have mentioned that one of the emerging challenges caused by the mobility of the sensor nodes is their network coverage. To deal with this issue WBANs should enclose multiple access points and support route variations in order to reach each sensor node. Moreover, to get continuous access to the sensor nodes, a valid route to each one at all times must be available. The mechanism to support the point of attachment change to the network is known as handover. One of the most difficult challenges in handover mechanisms is determining the exact moment at which to perform the attachment point change.

The energy harvesting sources in the human body can be either predictable (e.g. heart contractions or chest movement for breathing) or unpredictable (the motion of walking or the body temperature difference. The human energy harvesting capabilities should be considered in the design of new protocols an architectures (Ibarra, Antonopoulos, Kartsakli, & Verikoukis, 2013). However, the scarce energy collected by human motions, along with the strict requirements of vital health signals in terms of QoS, raises important challenges for WBANs and stresses the need for new integrated QoS-aware energy management schemes (Ibarra, Antonopoulos, Kartsakli, Rodrigues, & Verikoukis, 2016).

According to the aforementioned aspects and all main challenges, the selected challenges that will be tackled with the proposed architecture are: Energy Efficiency, Quality of Service, Reliability and Context awareness.

1.3 Research Objectives

1.3.1 General Objective

The main objective of this research project is to design a new reliable, context-aware and energy-efficient architecture for Wireless Body Area Networks, ensuring Quality of Service and fairness in Sports applications.

1.3.2 Sub-objectives

1. Designing a context-aware and energy-efficient mechanism for providing Quality of Service and reliability in Wireless Body Area Networks used in Sports applications.
2. Designing a reliable and energy-efficient mechanism for providing packet loss recovery and fairness in Wireless Body Area Networks used in Sports applications.
3. Designing a context-aware and energy-efficient rate control scheme for providing congestion control and fairness in Wireless Body Area Networks used in Sports applications.

1.4 Methodological Approach

For accomplishing the research objectives, the architecture was designed as a cross-layer solution, defining its assumptions, requirements and topologies. Then, it was divided in three main phases: (i) Designing of a MAC protocol (implemented over the Application and MAC layers) for providing context awareness, reliability and energy efficiency; (ii) Designing of a Transport protocol (implemented over the MAC layer) for providing loss recovery and fairness; and (iii) Designing of a rate control scheme (implemented over the Application and MAC layers) for providing congestion control and fairness.

The sub-objective one was accomplished with the design of a MAC protocol. The MAC protocol was made in two stages: (i) Designing of a MAC protocol for providing emergency awareness and energy efficiency; and (ii) Designing of a MAC protocol for providing context awareness, reliability and energy efficiency. A comparative analysis was made between the designed MAC protocol and the IEEE 802.15.6 Standard. For the evaluation, the designed MAC protocol was compared against a WSN MAC protocol called T-MAC (Timeout MAC), the IEEE 802.15.4 Standard MAC protocol and the IEEE 802.15.6 Standard MAC protocol.

The sub-objective two was accomplished with the design of a Transport protocol. The transport protocol was designed using the previously proposed MAC protocol. The designed transport protocol was comparatively analyzed against the IEEE 802.15.6 Standard in order to show the performance of the loss recovery. For the evaluation, the designed transport protocol was compared with the previously proposed MAC protocol and the IEEE 802.15.6 Standard.

The sub-objective three was accomplished with the design of a rate control scheme. The rate control scheme was designed using the previously proposed MAC protocol. For the evaluation, comparisons were made between the previously proposed MAC protocol and the IEEE 802.15.6 Standard with and without the use of the proposed rate control scheme for mitigating the packet congestion in the WBAN.

1.5 Main Contributions and Originality

The main contributions of this research project are presented as follows:

A new energy-efficient and emergency-aware MAC protocol for Wireless Body Area Networks. This new MAC protocol for WBANs is based on the existing MAC protocol described in the IEEE 802.15.6 standard, but with some modifications in the access phases and the access methods for each beacon period in order to provide more emergency awareness while keeping energy efficiency.

A new context-aware and reliable MAC protocol for Sports Wireless Body Area Networks. This new MAC protocol for WBANs is a cross-layer design and is based on the previously proposed MAC protocol, but taking into account the unique characteristics of sports WBANs where is not uncommon to have sporadic emergency traffic and a high amount of normal traffic. The proposed protocol emphasizes reliability and uses context awareness for changing transmission schedules while providing quality of service in emergencies and keeping energy efficiency.

A new reliable transport protocol based on loss recovery and fairness for Sports Wireless Body Area Networks. This new transport protocol is a cross-layer design that uses loss recovery and fairness to provide reliability. The protocol is based on the previously proposed MAC protocol. It detects out-of-sequence packets and requests retransmission of the lost packets. It outperforms the previously proposed MAC protocol and the IEEE 802.15.6 Standard in the percentage of the packet loss, while maintaining a similar energy consumption.

A new rate control scheme for congestion control in Sports Wireless Body Area Networks. This new rate control scheme is provided for mitigating congestion in WBANs and is based on the previously proposed MAC protocol. The scheme is context-aware and responses to emergency events in any node controlling the normal traffic rate. The proposed solution improves the performance of both the previously proposed MAC protocol and the IEEE 802.15.6 Standard.

A new reliable, context-aware and energy-efficient architecture for Wireless Body Area Networks used in Sports applications. The architecture put together the three solutions previously proposed: the MAC protocol, the transport protocol and the rate control scheme in order to offer reliability, context awareness and quality of service while keeping energy efficiency in the whole WBAN.

1.6 Organization of the Thesis

The remainder of this document is organized as follows:

Chapter 2 – Literature Review: this chapter presents a bibliographic review of WBAN solutions in each layer of the communication protocol stack. It also presents some cross-layer solutions, a brief of WSN and WBAN solutions, and some proposed architectures.

Chapter 3 – Energy-Efficient, Context-Aware and Reliable MAC Protocol for Sports Wireless Body Area Networks: this chapter presents a new MAC protocol for WBANs based on the existing MAC protocol described in the IEEE 802.15.6 Standard.

Chapter 4 – Reliable Transport Protocol based on Loss-Recovery and Fairness for Wireless Body Area Networks: this chapter presents a new transport protocol for WBANs used in sports applications. It is based on the energy-efficient and emergency-aware MAC protocol presented in Chapter 3.

Chapter 5 – Rate Control Scheme for Congestion Control in Wireless Body Area Networks: this chapter presents a new rate control scheme from mitigating congestion in WBANs based on the energy-efficient and emergency-aware MAC protocol presented in Chapter 3.

Chapter 6 – Proposed Architecture: this chapter presents the assumptions, the requirements, the topologies, and the proposed phases for the WBAN architecture. The architecture is evaluated through the comparison with other architectures. It also summarizes the whole architecture as the join of the three solutions previously proposed: the MAC protocol in Chapter 3, the transport protocol in Chapter 4 and the rate control scheme in Chapter 5.

Chapter 7 – Conclusion: this chapter highlights the main contributions of this research project, its limitations and the future research.

CHAPTER 2 LITERATURE REVIEW

Akyildiz et al. (2002) have proposed the Sensor Network Protocol Stack used by the sink node and the sensor nodes and it is depicted in the Figure 2.1. This protocol stack consists of five layers: the Application layer, the Transport layer, the Network layer, the Data link layer, the Physical layer; and three planes: Power management plane (how a sensor node uses its power), Mobility management plane (detecting and registering the movement of sensor nodes) and Task management plane (balancing and scheduling the sensing tasks given to a specific region).

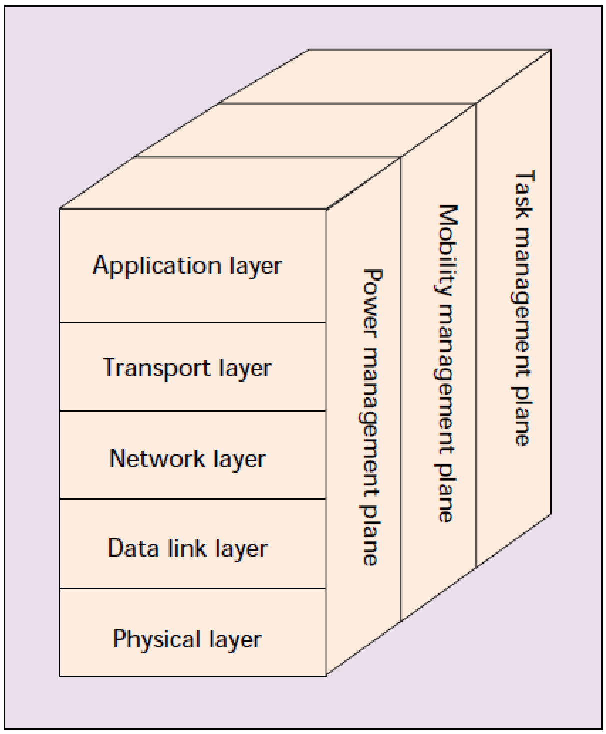

Figure 2.1. The Sensor Network Protocol Stack

We investigate the main challenges and related work for each layer of the communication protocol stack. First, in the Sections 2.1 to 2.5 we review the five layers of the protocol stack, highlighting some proposed protocols and solutions. Second, in the Section 2.6 we review some proposed cross-layer solutions. Finally, in the Section 2.7 we present a comparative analysis between WBANs and WSNs.

2.1 Physical Layer

The physical layer is responsible for frequency selection, carrier frequency generation, signal detection, modulation, and data encryption (Akyildiz et al., 2002). The physical schemes outlined by IEEE 802.15.6 Standard are: Human Body Communication, Narrowband, and Ultra-Wideband. Lai et al. (2013) present the WBAN Frequency bands used by the communication technologies and they are depicted in the Figure 2.2.

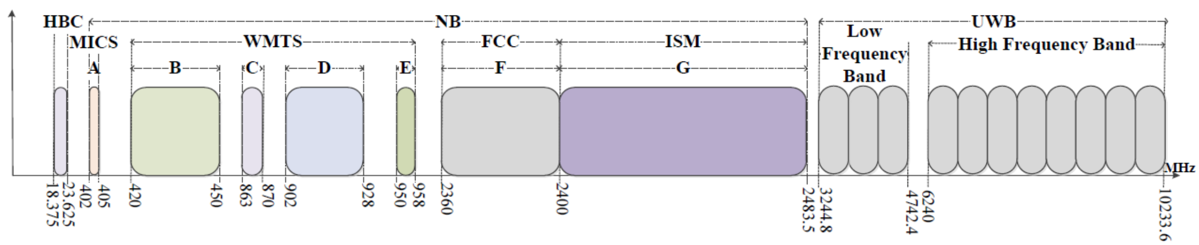

Figure 2.2. WBAN Frequency bands

2.1.1 Human Body Communication (HBC)

The HBC specification in the IEEE 802.15.6 Standard uses electric field communication (EFC) technology. It operates in two frequency bands centered at 16 and 27 MHz with bandwidth of 4 MHz (Cheffena, 2015). It takes the human body as the data transmission medium and is only used by WBANs. Seyedi et al. (2013) identify three desirable characteristics for Intra-Body Communication (IBC) technique: natural security and interference-free communication, low energy consumption, frequency reuse. Its primary technology is electric field coupling which includes capacitive coupling and galvanic coupling (Lai et al., 2013).

- Capacitive coupling: only one of the electrodes (signal electrode) of the transmitter side and receiver side is attached to the body while the other electrode (ground electrode) is floating. The signal is generated between the body channel transceiver by making a current loop through the external ground. The signal electrode of the transmitter induces the electric field into the human body.
- Galvanic coupling: both electrodes of the transmitter and the receiver side are attached to the human body. Galvanic coupling is achieved by coupling alternating current into the

human body. It is controlled by an alternating current flow and the body is considered as a transmission line (waveguide).

The authors have mentioned that the reliance of the ground capacitive coupling to complete the current loop means that the capacitive technique is more susceptible to noise interference compared to the galvanic method. Electromagnetic induction is commonly used when continuous, long-term communication is required, such as for a cochlear implant used to restore hearing. It achieves the best power transfer when using large transmitter and receiver coils. However, it is impractical when space is an issue or devices are implanted deep within the patient. Besides, Ullah et al. (2012) mention this technique does not support very high data rate applications and cannot initiate a communication session from inside the human body.

2.1.2 Narrowband (NB)

The NB layer in the IEEE 802.15.6 Standard is responsible for clear channel assessment, radio transceiver activation/deactivation and data transmission and reception. The NB physical layer does not support high data rate applications (Cheffena, 2015).

Medical Implant Communications Service (MICS), which has a transmission power of 25µW, is also one of communication bands suitable for low data-rate networks (Lai et al., 2013) (Ullah et al., 2012). The Wireless Medical Telemetry Service (WMTS) is mainly used in wireless telemetry in hospitals. The Federal Communication Commission (FCC) urges the use of WMTS by medical applications due to fewer interfering sources (Ullah et al., 2012). Band F is the 2.36GHz medical band approved by the FCC in the United States. The restricted WMTS (14 MHz) bandwidth cannot support video and voice transmissions, so the Industrial Scientific Medical (ISM) band commonly is used in WBANs operates at 2.4GHz (Lai et al., 2013) (Ullah et al., 2012).

2.1.3 Ultra-Wideband (UWB)

The UWB physical layer in the IEEE 802.15.6 Standard operates in both low and high frequency bands. The low band consists of three channels where channel 2 (mandatory channel) has a central frequency of 3993.6MHz. The high band has eight channels where channel 7 (mandatory) has a central frequency of 7987.2MHz (Cheffena, 2015). It is a technique with low-power and high data rate features. Its large bandwidth signals provide robustness to jamming with low probability of interception.

2.1.4 Network Topology

Lai et al. (2013) identify the most common network topologies as star topology, mesh topology, ring topology, and bus topology. The authors mention that both ring topology and bus topology are not fit for deploying on a complex dynamic human body and there is almost no application systems using these two topologies because the WBAN scale is small and sink nodes need to gather body information to send it to remote computers. Hence, star topology and mesh topology are the most used topologies for WBANs. The authors also provide a comparison between star topology and mesh topology and it is shown in the Table 2.1.

Table 2.1. A comparison between star topology and mesh topology

	Star Topology	**Mesh Topology**
Path Loss	Nodes on the same side with low path loss. Nodes on the different sides with high path loss.	Reducing path loss caused by diffraction through multiple hops.
Radio Transmission Range	Not suitable for small radio propagation range.	Adjusting radio propagation range by changing the number of nodes.
Energy Consumption	Nodes closer to sink node consume lower power.	The nodes nearer to sink node consume more energy, as they have to forward not only their data but also data from other nodes.
Transmission Delay	Sensors connect with sink node directly take the least possible delay in transmission.	Nodes closest to sink node get their data quickly, without any intermediate delay.
Inter-User Interference	Nodes farther away from sink node need higher power to transmit data with more interference to other nodes.	As each node only transmits to its neighbors, the energy of transmission is low and hence with smaller interference.
Node Failure and Mobility	Only the failed node is affected and the rest nodes of network perform well.	The whole network including nodes with errors need to be reset.

Chen et al. (2010) have identified some unique requirements for the design of physical protocols for WBANs:

- Seamless connectivity that needs to be maintained in dynamic environments in an attempt to realize the least possible performance degradation in terms of latency, data loss and throughput.
- In unlicensed bands, robust protocol design is needed to mitigate interference issues as induced by surrounding devices operating at a high transmission power.
- Power consumption should scale linearly as the data rate is increased in order to obtain a constant energy-per-bit information signal.

Sodhro, Li, and Shah (2016) have proposed an energy-efficient adaptive power control algorithm that adaptively adjusts transmission power levels based on the feedback from the base station. The main advantages of the proposed algorithm are saving more energy with acceptable packet loss ratio (PLR) and lower complexity in implementation of desired trade-off between energy savings and link reliability.

2.2 Data Link (MAC) Layer

The data link layer is responsible for the multiplexing of data streams, data frame detection, medium access and error control (Akyildiz et al., 2002). The original purpose of this layer is achieving maximum throughput, minimum delay, and to maximize the network lifetime by controlling the main sources of energy waste: collisions, idle listening, overhearing, and control packet overhead (Lai et al., 2013) (Ullah et al., 2012) (Hughes et al., 2012). A collision occurs when more than one packet transmits data at the same time. The collided packets have to be retransmitted, which consumes extra energy. Idle listening means that a node listens to an idle channel to receive data. Overhearing means receiving packets that are destined to other nodes. Control packet overhead means that control information is added to the payload. Therefore, a minimal number of control packets should be used for data transmission (Ullah et al., 2009).

Ullah et al. (2009) mention that generally, MAC protocols are divided into two groups:

- Contention-based (random access based) MAC protocols: i.e. Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) protocols, where nodes contend for the channel to transmit data. If the channel is busy, the node defers its transmission until it becomes idle. These protocols are scalable with no strict time synchronization constraint. However, they incur significant protocol overhead.

- Schedule-based (polling based) MAC protocols: i.e. Time Division Multiple Access (TDMA) protocols, where the channel is divided into time slots of fixed or variable duration. These slots are assigned to nodes and each node transmits during its slot period. Hughes et al. (2012) mention these protocols are energy-conserving protocols. Since the duty cycle of radio is reduced, there is no contention, idle listening and overhearing problems, but these protocols require frequent synchronization.

Hughes et al. (2012) add a new group of MAC protocols: Hybrid schemes, combining contention and scheduled methods as part of an adaptive scheme. This type of architecture can improve performance over existing schemes by adapting to network traffic conditions as they arise. A hybrid MAC can function in contention-based scheme mode when traffic is light and convert to a scheduled-based scheme when traffic is heavy.

J. Y. Khan et al. (2010) pose that if a node generates any urgent data in a non-scheduled manner, then a TDMA or scheduled-based system will have difficulties to transmit that data immediately. Whereas, as soon as any non-scheduled data is generated at a node the contention-based nodes can transmit the data provided that the node has the necessary priority. The main disadvantage of a contention-based protocol is that it could introduce a variable and longer delay if the traffic load in a network is high. If the traffic load remains fairly stable and lower than about 70% of a network capacity, then a contention-based protocol offers reasonably low and bounded delay.

(Ullah et al., 2012); Ullah et al. (2009) compare CSMA/CA and TDMA protocols and this is shown in Table 2.2.

Table 2.2. CSMA/CA vs. TDMA protocols

Performance Metric	**CSMA/CA**	**TDMA**
Power consumption	High	Low
Traffic level	Low	High
Bandwidth utilisation	Low	Maximum
Scalability	Good	Poor
Effect of packet failure	Low	Latency
Synchronisation	Not Applicable	Required

The MAC layer should support Multiple Physical layers (Multi-PHYs) communication. In other words, it should support the simultaneous operation on in-body (MICS) and on-body frequency bands/channels (ISM or Ultra-Wide Band - UWB) at the same time. Other important factors are scalability and adaptability to changes in the network, delay, throughput, and bandwidth utilization. Changes in the network topology, the position of the human body, and the node density should be handled rapidly and successfully. Besides, the MAC protocol for a WBAN should consider the electrical properties of the human body and the diverse traffic nature of in-body and on-body nodes (Ullah et al., 2009).

The energy efficiency is one of the most important factors for MAC layers in WBAN. Chen et al. (2010) have mentioned that body sensors have a very limited battery capacity, especially for those sensors which are placed inside the body. To increase the lifespan of these sensors, energy-efficient MAC protocols play an important role.

Ullah et al. (2012) have mentioned that for emergency applications, the MAC protocol should allow in-body or on-body nodes to get quick access to the channel (in less than one second) and sending the emergency data to the coordinator. One such example is the detection of an irregular heartbeat, high or low blood pressure or temperature, and excessively low or high blood glucose level in a diabetic patient. Reporting medical emergency events should have a higher priority than non-medical emergency (battery dying) events.

Chen et al. (2010); Hughes et al. (2012); Ullah et al. (2009) have listed some MAC protocols for WBANs:

- Body Sensor Network MAC (BSN-MAC) is a dedicated ultra-low-power MAC protocol designed for star topology WBANs. It adjusts protocol parameters dynamically to achieve best energy conservation on energy critical sensors.
- H-MAC is a TDMA-based MAC protocol designed for WBANs, which aims to improve energy efficiency by exploiting heartbeat rhythm information to perform time synchronization. Following the rhythm, biosensors can achieve time synchronization without having to turn on their radio to receive periodic timing information from a central controller. However, the heartbeat rhythm information varies depending on the patient condition and it may not reveal valid information for synchronization all the time.
- IEEE 802.15.4 is a low-power protocol designed for low data rate applications. Some of the main reasons of selecting IEEE 802.15.4 for a WBAN are low-power communication and support of low data rate WBAN applications. Since the IEEE 802.15.4 operates in the 2.4 GHz unlicensed band, the possibilities of interference from other devices such as

IEEE 802.11 and microwave are inevitable. Although 802.15.4 can provide QoS, the technology is not scalable in terms of power consumption and cannot be used as a single solution for all WBAN applications (Latré et al., 2011). Besides, it cannot support high data rate applications (>250 kb/s) and it targets at relatively long transmission distance (10–75m) (Bin, Zhisheng, & Chang Wen, 2013).

- Reservation-Based Dynamic TDMA Protocol (DTDMA) was originally proposed for normal (periodic) WBAN traffic where slots are allocated to the nodes which have buffered packets and are released to other nodes when the data transmission/reception is completed. For normal (periodic) traffic, the DTDMA protocol provides more dependability in terms of low packet dropping rate and low energy consumption when compared with IEEE 802.15.4. However, it does not support emergency and on-demand traffic.

- S-MAC is a synchronous protocol where the basic idea is for nodes to sleep periodically and have each node somehow aware of all other nodes sleeping patterns. It is designed to save energy by periodically switching between active and sleep states, thereby making trade-offs between energy and latency according to traffic conditions. It delivers significant energy improvements over 802.11 but the duty cycle is required to be synchronized to a specific traffic load. Thus its performance suffers under varying traffic loads.

- Timeout-MAC (T-MAC) is an adaptive energy-efficient MAC protocol for WSNs, which proposes an adaptive duty cycle that dynamically ends the active part of the cycle to reduce the energy wasted on idle listening (Van Dam & Langendoen, 2003). It shortens the active period if the channel is idle. The nodes will return to sleep mode if no packet is received during this window. T-MAC improves on S-MAC by listening to the channel for only a short time after the synchronization phase. T-MAC uses one fifth of the energy used by S-MAC. However these gains come at the cost of reduced throughput and increased latency.

- Preamble-based TDMA Protocol (PB-TDMA) has been proposed and the simulations have shown that it outperforms IEEE 802.15.4 protocol in terms of energy efficiency, but the results are valid for normal traffic only and do not consider the behavior of emergency and on-demand traffic.

- BodyMAC Protocol is a TDMA-based protocol where the channel is bounded by TDMA super-frame structures with downlink and uplink subframes. The downlink frame is used to accommodate the on-demand traffic and the uplink frame is used to accommodate the normal traffic. It accommodates the on-demand traffic using the downlink subframe. However, in case of low-power implants (which should not receive beacons periodically), the coordinator has to wake up the implant first and then send synchronization packets, but the wake up procedure for low-power implants is not defined in the protocol. Besides, there is no proper mechanism to handle the emergency traffic (Gengfa & Dutkiewicz, 2009).
- Body Area Network MAC (BANMAC) is a MAC protocol that monitors and predicts the channel fluctuations. It schedules transmissions opportunistically when the Received Signal Strength (RSS) is likely to be higher. The MAC protocol is capable of providing differentiated service and resolves co-channel interference in the event of multiple WBANs in vicinity (Prabh, Royo, Tennina, & Olivares, 2012).

In a WBAN, most of the traffic is correlated, i.e., a patient suffering from a fever triggers temperature, blood pressure, and respiration sensors at the same time. These changes may also affect the oxygen saturation level (SpO2) in the blood. These kinds of physiological parameters increase the traffic correlation. A single physiological fluctuation triggers many sensors at the same time. In this case, a CSMA/CA protocol encounters heavy collisions and extra energy consumption (Hughes et al., 2012; Ullah et al., 2009).

The Quality of Service (QoS) is also an important factor of a good MAC protocol for a WBAN. This includes point-to-point delay and delay variation. In some cases, real-time communication is required for many applications such as fitness and medical surgery monitoring applications. Chen et al. (2010) have also identified some representative works in Quality of Service (QoS) provisioning:

- BodyQoS aims to provide QoS in WBANs with prioritized data stream service, asymmetric QoS framework, radio-agnostic QoS, and Adaptive Bandwidth Scheduling. It consists of three components: Admission Control, QoS Scheduler and a Virtual MAC (VMAC).

- The Distributed Queuing Body Area Network (DQBAN) MAC protocol aims at providing better QoS support. It uses a cross-layer fuzzy rule based scheduling algorithm to optimize MAC layer performance in terms of QoS and energy efficiency.
- Employing the IEEE 802.15.4 Beacon-enabled mode for QoS provisioning, researchers have proposed a QoS provisioning framework for WBAN traffic using the corresponding super-frame structure. The framework utilizes both the contention access periods (CAP) for time-critical traffic, and guaranteed time slots (GTS) in contention-free periods (CFP) for periodic traffic.

Yan and Dolmans (2009) have proposed a priority-guaranteed MAC protocol for WBANs. This protocol adopts dedicated control channels to make the data channels collision free in order to support high data rate communications. Control channels are split into application-specific sub-channels, and hence the access contention is restricted to the same application category. Al Ameen, Ullah, Chowdhury, Islam, and Kwak (2012) have proposed a MAC protocol for WBANs using on-demand wake-up radio through a centralized and coordinated external wake-up mechanism. The protocol improves the power efficiency and delay.

Junsung and Jeong Gon (2013) have proposed an energy-efficient MAC protocol for WBAN through flexible frame structure. It is based on superframe structure, and it is subdivided by four steps. First, the hub receives a beacon from each node with the node data transmission information and data size. Second, the hub carries out synchronization with each node based on the data transmission information. Third, a channel's schedule is created in order to assign the channel between the hub and each node. The final step is where data transmission is controlled while the channel is being assigned and connection is established based on the channel schedule. If data exists in EAP1 but no data exists from the following RAP1, the node would be changed to the sleep mode after sending data on EAP1. In this way, energy consumed by the node can be saved. Since information is exchanged only when a mutual channel is established, QoS cannot be guaranteed.

Tobón, Falk, and Maier (2013) present some context-aware solutions into the MAC layer. The authors mention three MAC protocols like a TDMA-based protocol, to guarantee real-time transmission of life-critical data; and TAD-MAC (Traffic-Aware Dynamic MAC) protocol, where each node can adapt its wake-up interval with respect to all neighboring nodes according to given traffic variations.

Rezvani and Ghorashi (2013) have proposed a context-aware and channel-based resource allocation for WBANs. The authors use an adaptive resource allocation and traffic prioritization according to the medical situation of user and channel condition. Based on the transmission cycle, the authors divide medical nodes in permanent nodes (which transmit every beacon period) and impermanent nodes (with the transmission cycles greater than one beacon period). The authors change the predetermined transmission cycle of a medical sensor node when an emergency happens for that node.

Otal, Alonso, and Verikoukis (2009) have proposed DQBAN (Distributed Queuing Body Area Network), a novel cross-layer fuzzy-rule scheduling algorithm with energy-aware radio activation policies. The main idea is the integration of a fuzzy-logic system in each body sensor to deal with multiple cross-layer input variables of diverse nature in an independent manner. DQBAN operates as (i) a slotted Aloha protocol for light traffic load; (ii) a reservation protocol for high traffic load; and (iii) a “polling” protocol to guarantee — “on demand” — a collision-free “data slot”.

Hyosun and Nak Myeong (2012) have proposed an enhanced Continuous Frame Transmission (CFT) method to increase the energy efficiency of ultra-low-power devices under strong interference. CFT is a hybrid TDMA and random access MAC protocol with carrier sensing method. CFT controls the frame transmission bunches considering the effect of interference that changes according to the number of neighbor wireless devices.

Bin, Zhisheng, and Chang Wen (2011) have presented CA-MAC, a Context-Aware MAC protocol that is able to adopt different transmission strategies depending on the variation of patient activity, vital life signs, or environment status. The protocol is designed around a hybrid frame structure, a channel-aware adjustment of access mechanisms, and traffic-aware adjustment of transmission priority. The protocol incorporates a hybrid approach to channel access using a TDMA and contention-based model to reduce energy consumption and latency, allowing to the priority nodes to obtain a higher duty cycle and to be allocated more slots for data transmission.

Beacon packets are broadcast to define the frame structure in every frame. This could cause excessive control packet overhead.

Liu, Li, Yuan, and Liu (2015) have proposed an energy-efficient MAC protocol named Quasi-Sleep-Preempt-Supported (QSPS) which is mainly TDMA-based. The nodes transmit packets in the allocated slots, while entering the Q-Sleep mode in other slots. Moreover, for a node with emergency packet, it can broadcast a special designed Awakening Message to wake up the whole network and to preempt the right to use the current slot to transmit that emergency packet, thus decreasing delay.

F. Wang et al. (2015) have proposed an energy-efficient MAC protocol for WBANs based on human body posture under walking scenery. The posture-aware dynamic protocol for lifetime maximization (PA-DPLM) exploits the posture and local information of both channel state and residual energy.

2.3 Network Layer

The network layer is responsible for providing special multi-hop wireless routing protocols between the sensor nodes and the sink node (Akyildiz et al., 2002). Although MAC protocols can solve many problems in WBANs, they do not cover addressing and end-to-end package delivery problems which rely on routing protocols (Lai et al., 2013).

Ullah et al. (2012) have identified the specific characteristics of the wireless environment on the human body:

- The available bandwidth is limited, shared and can vary due to fading, noise and interference.
- The nodes that form the network can be very heterogeneous in terms of available energy or computing power.
- An extremely low transmit power per node is needed to minimize interference to cope with health concerns and to avoid tissue heating.
- The devices are located on the human body that can be in motion (changes in the network topology).

Ullah et al. (2012) have also given an overview of existing routing strategies for WBAN. These can be categorized into three groups:

- Temperature based routing: the radiation absorption and heating effects on the human body are important issues when considering wireless transmission around and on the human body. To reduce tissue heating, the radio's transmission power can be limited or traffic control algorithms can be used. The bio-effects caused by radio frequency radiation are highly related to the incident power density, network traffic and tissue characteristics. Another approach is to balance the communication over the sensor nodes.
- Cluster based routing: protocols can use clustering to reduce the number of direct transmissions to the remote base station, selecting a cluster head at regular time intervals in order to spread the energy dissipation. The cluster head aggregates all data and sends it to the base station.
- Cross-layer-based routing: Cross-layer design is a way to improve the efficiency of and the interaction between the protocols in a WSN by combining two or more layers from the protocol stack. One example of cross-layer protocol specifically designed for WBANs is CICADA (Cascading Information retrieval by Controlling Access with Distributed slot Assignment). It uses the same packets to take care of both medium access as well as routing. The packets are used to detect the presence or absence of the children and to control medium access. The protocol sets up a spanning tree and divides the time axis in slots grouped in cycles in order to lower the interference and to avoid idle listening (Ullah et al., 2012). CICADA-S became one of the first protocols where appropriate security mechanisms are incorporated into the communication protocol while addressing the lifecycle of the sensors (Latré et al., 2011).

Lai et al. (2013) present a summary of existing WBAN routing protocols and it is shown in the Table 2.3 with the resolved issues.

Table 2.3. Summary of existing WBAN routing protocols

Protocol	Content	Resolved Issues
FPSS	Choosing path intelligently among nodes based on heuristic self-adaptive algorithm in energy constrained on-body network.	Energy balance
PRPLC	Forwarding packets to proper neighbors by prediction	Topological partition

Protocol	Content	Resolved Issues
	of postural trends based on link likelihood fact.	
TARA	Establishing route to detour around hotspots area using a withdrawal strategy.	Minimizing the thermal effects of Implanted biosensors
LTR	Always choosing neighboring nodes with the lowest temperature as next stop.	
ALTR	Choosing next stop by both the lowest temperature node and the shortest hop count.	Implanted biosensors
LTRT	Choosing the shortest path based on a Dijkstra algorithm with the weight of temperature.	Implanted biosensors

Maskooki, Cheong Boon, Gunawan, and Low (2015) have proposed an adaptive routing protocol for WBANs. It minimizes the energy cost per bit of information by using the channel information to choose the best strategy to route data. In this approach, the source node will switch between direct and relayed communication based on the quality of the link and will use the relay only if the channel quality is below a certain threshold.

Rui, Dingjuan, Pathmasuntharam, and Yong Ping (2015) have proposed an opportunistic relay protocol with dynamic scheduling for WBANs. The protocol uses a predefined relaying node active during the data relaying process even if it is not elected. It achieves 50% reduction in data relaying failure rate, which in turn improves the packet delivery rate (PDR).

2.4 Transport Layer

This layer is especially needed when the system is planned to be accessed through the Internet or other external networks (Akyildiz et al., 2002). Traditional transport layer protocols such as Transmission Control Protocol (TCP) and User Datagram Protocol (UDP) are too heavyweight and complex for WBAN applications resulting in latency and excessive energy wastage for low power wireless networks. Protocols need to provide end-to-end reliability, QoS in an energy-efficient way and be evaluated using metrics such as Packet Loss Ratio (PLR), latency, and fairness. Therefore, transport protocols should have components for congestion control and loss recovery since these two components have a direct impact on energy efficiency, reliability, and QoS (Hughes et al., 2012).

Since healthcare applications deal with life-critical data, a lost frame or packet can cause an alarm situation to be missed totally or misinterpreted. Consequently, reliable data delivery is required. Although there are reliability mechanisms at different layers such as automatic repeat request (ARQ) at MAC layer, critical WSN applications such as healthcare monitoring require total end-to-end reliability mechanisms. Designing cross-layer protocols for ensuring reliable delivery for different types of traffic is essential (Alemdar & Ersoy, 2010).

There are several transport protocols specifically designed for WSNs. Chonggang, Sohraby, Bo, Daneshmand, and Yueming (2006) have categorized them in three groups: protocols for congestion control, protocols for reliability, and protocols for both congestion control and reliability.

Congestion Detection and Avoidance (CODA) is an energy-efficient congestion control scheme for WSNs that comprises three mechanisms: (i) Receiver-based congestion detection – it uses a combination of the present and past channel loading conditions, and the current buffer occupancy, to detect congestion at each receiver with low cost; (ii) Open-loop, hop-by-hop backpressure – a node broadcasts backpressure signals as long as it detects congestion. Backpressure signals are propagated upstream toward the source; and (iii) Closed-loop, multisource regulation – it is capable of asserting congestion control over multiple sources from a single sink in the event of persistent congestion (C.-Y. Wan, Eisenman, & Campbell, 2011).

Event-to-Sink Reliable Transport (ESRT) is a WSN transport protocol that guarantees event reliability through end-to-end rate adjustment. The end-to-end rate adjustment in ESRT follows two basic rules: if the current reliability perceived at the sink exceeds the desired value, ESRT will multiplicatively reduce the source rate. Otherwise, the source rate is additively increased if the required reliability is not met, unless there is congestion in the network (Akan & Akyildiz, 2005).

In Reliable Multi-Segment Transport (RMST) protocol for WSNs, the reliability refers to the eventual delivery to all subscribing sinks of any and all fragments related to a unique RMST entity. A unique RMST entity is a data set consisting of one or more fragments coming from the same source. Receivers are responsible for detecting whether or not a fragment needs to be resent (Stann & Heidemann, 2003).

Pump Slowly Fetch Quickly (PSFQ) provides reliable transport for WSNs. It uses NACK-based (Negative Acknowledgement) loss detection and notification, and local retransmission for loss recovery. In pump operation, the sink slowly and periodically broadcasts packets to its neighbors until all data fragments have been sent out. In fetch operation, a sensor node goes to fetch mode once a sequence number gap in a file fragment is detected. Finally, in report operation, the sink provides the sensor nodes' feedback information on data delivery status through a simple and scalable hop-by-hop reporting mechanism (Chonggang et al., 2006).

Improved Rate-Controlled Reliable Transport (IRCRT) protocol for WSNs, consists of four major components including: congestion detection, rate adaptation, rate allocation and end-to-end retransmission. IRCRT implements a NACK-based end-to-end loss recovery scheme. The sink maintains a list of missing packets per flow. When losses are detected, the sequence numbers of the lost packets are inserted into this list. Entries in this list of missing packets are sent as NACKs by the sink to each source. In this protocol, nodes can go to OFF state, and when a node is OFF, sink does not allocate any rate to it, so other nodes can use better from the channel capacity. When any part of network becomes congested, this protocol only decreases the rate of nodes that are in the congested part, not all nodes, increasing the channel utilization (Akbari & Yaghmaee, 2010).

Some authors have categorized the congestion in WSNs as contention-based and buffer-based. The contention-based congestion occurs when many nodes within range of one another attempt to transmit simultaneously and provoke packet collisions. The buffer-based congestion happens when the buffer in the hub or any node overflows and causes congestion and packets losses (Kafi, Djenouri, Ben-Othman, & Badache, 2014; Sergiou, Antoniou, & Vassiliou, 2014).

The congestion control schemes follow three steps starting by its detection, then, the corresponding notification and finally the appropriate mitigation. There are several congestion detection strategies: packet loss, buffer length, channel load, packet service time, channel busyness ratio and delay. The congestion notification can be implicit (into the data packet header) or explicit (into specific control messages). The congestion mitigation can be applied to the traffic originated in each node (decreasing the node rate) or to the network resources (exploiting idle resources). Congestion control schemes can also be categorized in three classes: congestion mitigation, congestion avoidance and reliable data transport (Kafi et al., 2014; Sergiou et al., 2014).

Priority-based Congestion Control Protocol (PCCP) is a congestion control approach for WSNs that uses flexible and distributed rate adjustment in each sensor node considering that sensor nodes may have different importance and need different throughput. A sensor node with a higher priority index enjoys a higher bandwidth and also sensor nodes that inject more traffic get more bandwidth (Kafi et al., 2014; Sergiou et al., 2014).

Enhanced Congestion Detection and Avoidance (ECODA) is a WSN protocol where packets are dynamically prioritized, using their initial static packet priority, delay and hop-count. When receiving a back-pressure message, the source node decreases its rate, or adjusts the rate for different paths if there are multiple of them (Kafi et al., 2014).

Adaptive Rate Control (ARC) is a WSN protocol that treats contention in event and periodic applications by introducing a random delay (back off) at the application layer before transmitting packets. ARC uses packet loss as collision or congestion indication at each hop to adjust the transmission rate of periodic applications. ARC maintains two independent sets for source traffic and transit traffic respectively, in order to guarantee fairness (Kafi et al., 2014; Sergiou et al., 2014).

Energy Efficient Congestion Control (EECC) is a source rate congestion control protocol for WSNs. Each node adds its current weight, which is defined as the product of the channel busyness ratio and the buffer occupancy, to the packet received from its children, and passes the packet to its parent. The sum of such weights is then used. When buffer size and channel busyness ratio reach their higher threshold, the node sets the congestion notification bit in every data packet sent. By receiving this notification, the parent calculates the new rate and informs its children nodes (Kafi et al., 2014).

Although WBANs are a subset of WSNs, there are important differences between them. Reliability and energy efficiency are essential in both networks. However, WBANs require higher security, sensor integration, miniaturization and human compatibility, support of topology changes due to human body movement, early event detection for emergency states, and context awareness for responding based on the current situation. The primary concern of conventional WSNs is energy saving rather than QoS, which, however, is essential in WBANs. It could be concluded that MAC and Transport layer protocols for WSNs cannot be directly used in WBANs (Tobón et al., 2013; Ullah et al., 2012).

Group-based Reliable Data Transport (GRDT) is a protocol that adopts TDMA and FDMA (Frequency Division Multiple Access) schemes to control channel access in WBANs. It provides block feedback message scheme instead of synchronous ACK for hop-by-hop loss recovery mechanism, which reduces transmission delay and improves the packet reception rate (Daoqu et al., 2010). Some authors have considered FDMA as a scheme that offers a collision-free medium, but that requires additional circuitry to communicate with different radio channels. This requirement could increase the cost of the sensor nodes (Demirkol, Ersoy, & Alagoz, 2006).

Samiullah, Abdullah, Bappi, and Anwar (2012) have proposed a transport layer protocol for energy-efficient congestion control and reliable data transfer in WBANs. The proposed protocol checks the queue length of its successor nodes and itself to determine congestion levels.

Kathuria and Gambhir (2014) have proposed a transport protocol for WBANs structured to overcome some QoS problems related to this layer like packets handling, reliable packet transmission with loss recovery and congestion control. The intention of the proposed schema is to provide end-to-end bidirectional (both upstream and downstream) and bi-functional (both packet-based and event-based) reliability.

Gambhir, Tickoo, and Kathuria (2015) have proposed a transport protocol for WBANs based on queue occupancy with the packet loss for controlling congestion. The proposed scheme consists of two main phases: (i) Quick Start – it begins with more number of packets in the beginning; and (ii) Congestion control module – composed of three sub-phases: Congestion Detection, Congestion Notification and Congestion Avoidance.

A transport protocol for WBANs based on queue occupancy and packet loss for controlling congestion has been proposed by Gambhir et al. (2015). The proposed scheme consists of two main phases: a quick Start for beginning with more number of packets, and a congestion control module composed of three sub-phases: congestion detection, congestion notification and congestion avoidance.

Another congestion control scheme based on fuzzy logic in WBANs has been proposed by Ghanavati, Abawaji, and Izadi (2015). The proposed system is able to detect congestion by considering local information such as the buffer capacity and the node rate. In case of congestion, the proposed system differentiates between vital signals and assigns priorities to them based on their level of importance.

Misra, Moulik, and Han-Chieh (2015) have proposed a cooperative game theoretic approach for data-rate tuning among sensors in a WBAN. This approach tune the data-rates based on certain parameters like criticality index, failure probability, power consumption ratio, along with the minimum demands of the sensors. It leads to a better tuning that specially takes care of the criticality of measured physiological data, through increasing the data-rate for critical sensor nodes by 10% on average.

2.5 Application Layer

The application layer for a WBAN includes the application running on the node that may be specific to the sensor type as well as management, security, synchronization, and query type functions. Any application-specific QoS constraints, e.g., latency, are handled at this level together with any data compression and signal processing. At the application layer system administrators can interact with the nodes by using a Sensor Management Protocol (SMP). A SMP enables the lower layers to transparently interface with the application layer to undertake key management tasks such as management of rules relating to attribute naming and clustering, time synchronization and authentication, sensor query and data dissemination (Hughes et al., 2012).

Alemdar and Ersoy (2010) have mentioned that organizing the data and producing meaningful information that evolves into knowledge is one of the hardest challenges at the application layer. The organization of ambient sensor data, medical data and other contextual data must be held by this layer. The authors also highlight that users should embrace the system for full satisfaction. Hence, the development of natural interfaces between a diverse group of people and pervasive systems is crucial.

Hanson et al. (2009) have identified some requirements in order to get widespread WBAN adoption:

- Value: the WBAN must improve the user’s quality of life.
- Safety: wearable and implanted sensors will need to be biocompatible and unobtrusive and have fault-tolerant operation.
- Security: the WBAN must provide security measures such as user authentication.
- Privacy: encryption will be necessary to protect sensitive data.
- Compatibility: the WBAN nodes need to interoperate with other WBAN nodes, existing inter-WBAN networks, and even with electronic health record systems.

- Ease of use: the WBAN nodes will need to be small, unobtrusive, ergonomic, easy to put on, few in number, and even stylish.

Training schedules of professional athletes and Entertainment

WBANs are mainly used for motion recognition and physiological status detection, which can help athletes with scientific training, posture correcting and skill improvement (Lai et al., 2013). Motion sensors can be worn at both hands and elbows, for accurate feature extraction of sports players' movements. Recent research has promoted the use of accelerometers placed on different body areas in order to identify specific postures. With this technology, players in many sports, such as golf, football, and cricket, can easily improve their performance and avoid injuries due to incorrect postures (Chen et al., 2010).

Tobón et al. (2013) have mentioned ABI research has recently reported that by 2017 60% of WBANs will be geared towards fitness, performance, and wellness tracking. This comes as no surprise as sleep, stress, and obesity are three global public health problems. WBANs may be used to monitor fitness-related activities, including several sensors for measuring different physiological parameters, like heart rate, energy consumption, fat percentage (bio-resistance meter), body water content or galvanic skin response. Sports applications demand for high-capacity systems to deliver real-time information (Oliveira, Mackowiak, & Correia, 2011).

A flexible, textile capacitive sensor fabricated from conductive textile patches to measure capacitance of the human body could reveal information of human activities such as including heart rate and breathing rate monitoring, hand gesture recognition, swallowing monitoring, and gait analysis (Mukhopadhyay, 2015).

Body sensors enable game players to perform actual body movements, such as boxing and shooting, that can be feedback to the corresponding gaming console, thereby enhancing their entertainment experiences (Chen et al., 2010).

Medical Treatment and Diagnosis

Hanson et al. (2009) consider that WBAN research has concentrated on healthcare applications, addressing the weaknesses of traditional patient data collection, such as imprecision (qualitative observation) and under-sampling (infrequent assessment).

Health and motion information are monitored in real-time, and delivered to nearby diagnosis or storage devices, through which data can be forwarded to off-site doctors for further processing (Chen et al., 2010). The data obtained during a large-time interval in the patient's natural environment offers a clearer view to the doctors than data obtained during short stays at the hospital (Latré et al., 2011). Alemdar and Ersoy (2010) have posed that remote monitoring capability is the main benefit of pervasive healthcare systems. Providing real-time identification and action taking in pervasive healthcare systems are among the main benefits.

Barakah and Ammad-uddin (2012) have presented some examples of combinations of sensors that can be used for medical applications:

- Cardiovascular Disease (CVD): it includes pulse oximeter, heart rate sensors, and ECG sensors. The corresponding medical staff can make treatment preparation in advance as they receive vital information regarding the heart rate and irregularities of the heart while monitoring the health status of the patient.
- Paraplegic: it includes accelerometer, gyroscope, sensors for legs position, sensors attached with nerves, actuators positioned on the legs that can stimulate the muscles. Interaction between the data from the sensors and the actuators makes it possible to restore the ability to move.
- Diabetes: it includes blood glucose monitor and insulin actuators. If the sensor monitors a sudden drop of glucose, a signal can be sent to the actuator in order to start the injection of insulin. Consequently, the patient will experience fewer nuisances from his disease.
- Visually impaired: it includes artificial retina, matrix of micro sensors and external cameras. An artificial retina, consisting of a matrix of micro sensors, can be implanted into the eye beneath the surface of the retina. The artificial retina translates the electrical impulses into neurological signals. The input can be obtained locally from light-sensitive sensors, or by an external camera mounted on a pair of glasses.
- High Blood pressure: it includes blood pressure sensors and actuators with medicine. If the sensor monitors a change in blood pressure more than a threshold value, a signal can be sent to the actuator in order to start the injection medicine. Consequently, there is less chance of strokes.

- Parkinson's disease: it includes motion sensors and accelerometers. It estimates the severity of tremor, bradykinesia, and dyskinesia from accelerometer data and performs a thorough assessment.
- Postoperative monitoring: it includes temperature sensors, blood pressure sensor, heart rate sensors, and ECG sensors. The patient will no longer need to stay in bed, but will be able to move around freely.

Quality of life can be significantly improved, in particular for patients suffering from chronic diseases that require permanent monitoring of vital signs. WBANs may allow the detection of the early signs of disease and monitoring transient or infrequent events (Oliveira et al., 2011). KNOWME is a platform for monitoring and evaluation of physical activity of pediatric obesity patients. The fundamental hypothesis of the project is that the movement descriptors captured using inertial sensors could be used to estimate the caloric expenditure (Mitra et al., 2012). The LOBIN project has been defined as a healthcare IT platform to both monitor several physiological parameters (ECG, HR, angle of inclination, activity index and body temperature) and track the location of a group of patients within hospital facilities (Custodio, Herrera, López, & Moreno, 2012).

Safeguarding of uniformed personnel

A WBAN employed for military operations has the following roles: (i) ensuring that adequate water is delivered and consumed, (ii) reducing the likelihood of body harm attributed to harsh environmental conditions, such as heat stroke, and (iii) improving the quality of medical care in the event of an injury (Chen et al., 2010). An amperometric sensor composed of a multiwall carbon nanotube functionalized nylon-6 can help to quantify the amount of sodium ions in sweat in real-time (Mukhopadhyay, 2015).

A battle dress uniform integrated with a WBAN may become a wearable electronic network that connects devices such as life support sensors, cameras, RF and personal PDAs, health monitoring GPS, and transports data to and from the soldier’s wearable computer. The network could perform functions such as chemical detection, identification to prevent casualties from friendly fire and monitoring of a soldier’s physiological condition. Calling for support, his radio sends and receives signals with an antenna blended into his uniform (Ragesh & Baskaran, 2012).

2.6 Cross-layer Design

Some reasons why the traditional layered approach to network design has been questioned are enumerated by Hughes et al. (2012): network heterogeneity, QoS, channel conditions and performance. Most cross-layer schemes involve the communications between different adjacent or non-adjacent layers of the protocol stack to improve the performance in some way over the traditional layered approach. These performance gains can be in the form of energy efficiency, reduced contention, better routing decisions or improved reliability. In a network with multiple nodes all contending for resources, if no arbitration is enforced, QoS constraints can be breached. A traditional solution to this problem is to use the transport layer to perform congestion control, find the best path via an effective routing algorithm at the network layer, and use of the MAC protocol to access the channel to give the best single-hop performance. However, this type of mechanism can never deliver optimal performance as the algorithms in the various layers are not optimized together.

Oliveira et al. (2011) mention that at the upper layers, compression and aggregation of data should be exploited under a power aware strategy, but taking the application into account (e.g., aggregation is not reasonable for streaming, but it is suitable for monitoring applications). Since transmission is a major energy consumer, a substantial reduction could be made by intelligent processing, compressing the signal or extracting only its significant features, while removing the characteristic artefacts caused by (inevitable) body influence (absorption and antenna displacement). Exploiting temporal and spatial correlation is likewise pertinent, e.g., observed signals might vary only slowly in time.

The authors also highlight that a careful trade-off between communication and computation is crucial for an optimal node design, which should be applied at both sensor and sink (body central unit) nodes. At the network layer, bottlenecks resulting from sudden increases of the network load should be avoided, such as after an emergency event. If the network throughput suffers, there is no guarantee that all the critical information is going through the network. At the data-link layer, energy can be saved by intelligent and power-aware MAC protocols, which have to be adapted to the different applications requirements. A true cross-layer protocol design is desired for WBANs, achieved by actively exploiting the dependence between the different protocol layers in order to obtain performance gains. Instead of reaching particular optimizations for each layer treating them independently, a holistic solution can be found, hence, optimizing interactions between layers.

Hughes et al. (2012) identify QoS requirements within a WBAN as: high PDR, low levels of packet transmission delay, minimal collisions and retransmissions and efficient balancing of high energy efficiency and reliable transmission. Optimized energy efficiency requires an energy management process that efficiently balances QoS with energy efficiency, adapting to heterogeneous node constraints and wireless channel dynamics. QoS can only be evaluated at the higher layers of the protocol stack while energy consumption largely appears at the lower layers. Protocols working at each of the layers need to contribute to low packet transmission delay, minimum jitter, extremely low levels of congestion, low energy usages, while fulfilling specific QoS demands.

Omeni, Wong, Burdett, and Toumazou (2008) have proposed an energy-efficient MAC protocol for WBANs with cross-layer functionalities. The protocol breaks large packets into smaller frames and transmits them one at a time. The receiver is able to reassembles the fragmented data. Depending on the application, the protocol can control the frequency and the rate of sensor data acquisition.

Hughes et al. (2012) have presented a summary of low power cross-layer protocols which is shown in Table 2.4.

Table 2.4. Low power cross-layer protocols

Protocol	Protocol Summary
CAEM	Allows a node to dynamically adjust data throughput by changing levels of error protection at the node according to quality of the link, estimated bandwidth, and traffic load. Protocol buffers the packet until the channel recovers to the required quality. Performance gains of up to 30% compared to traditional protocols.
CoLaNet	Incorporates the characteristics of the application to make better routing path choices at the network layer and demonstrated energy savings over S-MAC.
TICOSS	Based at 802.15.4. Network is divided into time zones where each one takes turn in transmitting. Mitigates the hidden node problem, provides configurable shortest path routing to the BCU and almost doubles node lifetime for high traffic scenarios compared to other standard protocols.
SCSP	Dynamically calculates node sleep and data receive periods depending on traffic levels. MAC layer provides the list of neighbor nodes to the network layer, which in turn provides multiple forwarding choices to it. Switches between active and sleep periods by dynamically adapting modes depending on traffic levels. Uses a simple routing protocol that doesn't need route maintenance or discovery. Extends

Protocol	Protocol Summary
	the network lifetime and connectivity in comparison with 802.15.4.
QoS Adaptive Cross-layer Congestion Control	Incorporates an adaptive cross-layer mechanism to control congestion for real and non-real-time data flow to support QoS guarantees at the application layer. Priority given to real-time data for delay and available link capacity. Scheme links the QoS requirements at the application layer and packet waiting time, collision resolution, and packet transmission time metrics at the MAC layer.
CC-MAC	Cross-layer solution incorporating the application and MAC layers. Exploits the spatial correlation between nodes to reduce energy consumption without compromising reliability at the sink. Delivers improved performance over S-MAC and T-MAC in terms of energy efficiency, packet drop rate, and latency.
XLP	Extends XLM and merges the functionalities of traditional MAC, routing and congestion control into a unified cross-layer module by considering physical layer and channel effects avoiding the need for end-to-end congestion control.

Congestion Control and Fairness (CCF) is a many-to-one routing protocol for WSNs that modifies its rate using the packet service time which is the period between sending the packet at the transport layer to the network layer and the reception of successful transmission notification. CCF controls congestion in a hop-by-hop manner and each node uses exact rate adjustment based on its available service rate and child node number (Kafi et al., 2014; Sergiou et al., 2014).

XLM is a cross-layer protocol for WSNs that fuses communication layers into a single protocol to minimize energy consumption, adapt communication decisions, and avoid congestion. A node initiates a transmission by the broadcast of an RTS (Request to Send) with its location and that of the hub. By the reception of the RTS, each neighbor that is closer to the hub decides upon its participation according to the Signal to Noise Ratio (SNR), the remaining energy and its available buffer space. If no RTS are received because of network congestion, the node multiplicatively decreases its generated rate. Otherwise, the generated rate is linearly increased for each received acknowledgement (Kafi et al., 2014).

Priority-based Coverage-aware Congestion (PCC) control protocol is a hop-by-hop mechanism at the network and MAC layers of a WSN. Nodes generate periodic packets at a constant rate until an event happens, where nodes generate event packets with higher rate and priority. Intermediate nodes forward the packets with a different priority using this indication (Kafi et al., 2014).

Several congestion control algorithms for WSNs have been designed across the transport and MAC layers and even the network layer for efficient congestion detection and control. The cross layer design, by the interaction between different layers, helps in enhancing sensor networks protocols (Kafi et al., 2014). Upstream Hop-by-Hop Congestion (UHCC) is a control protocol based on a cross layer design for WSNs that tries to reduce packet losses while guaranteeing priority-based fairness with lower control overhead. Based on the congestion index every upstream traffic rate is adjusted with its node priority to mitigate congestion hop-by-hop (Sergiou et al., 2014).

2.7 WBANs vs. WSNs

Chen et al. (2010) have identified some differences between WBANs and WSNs:

- Deployment and Density: typically, WBAN nodes are placed strategically on the human body, or are hidden under clothing and are not node-dense, whereas WSN nodes are often deployed at places that may not be easily accessible.
- Data Rate: WBANs are employed for registering a human's physiological activities and actions, which may occur in a more periodic manner than events monitored by WSNs.
- Latency: high latency is not acceptable for WBANs.
- Battery life: it may be necessary to maximize battery life-time in a WSN, whose nodes can be physically unreachable after deployment, producing higher latency. Replacement of batteries in WBAN nodes is sometimes easier done for the wearable sensors than WSN nodes.
- Mobility: WBAN nodes share the same mobility pattern, unlike WSN nodes that are usually considered stationary.

Tobón et al. (2013) have mentioned the main challenges considered for WBANs compared with WSNs and they are depicted in the Figure 2.3. It can be seen that both types of network share only three main challenges: reliability, energy efficiency and cost structure. Some very important challenges for WBANs like early event detection, security, context awareness and topology changes are not so important for WSNs.

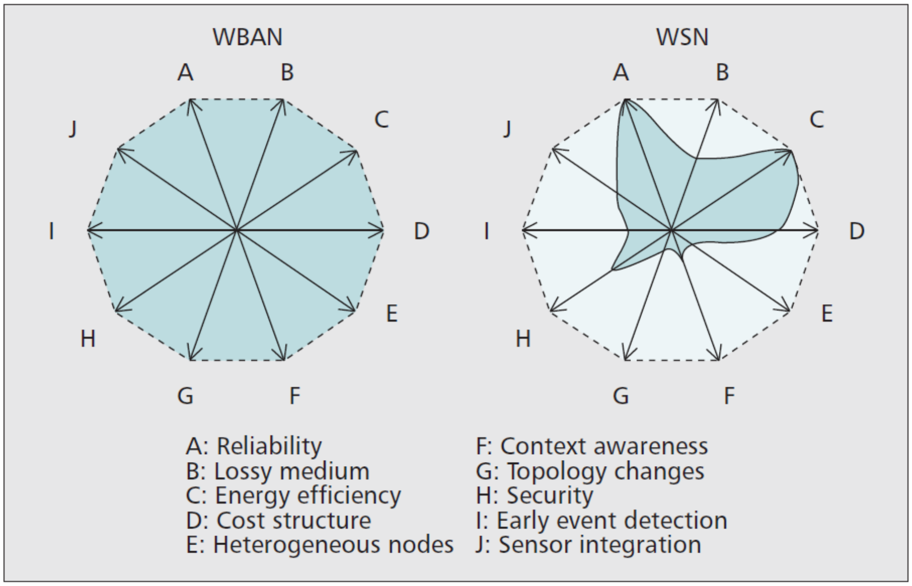

Figure 2.3. WBANs vs. WSNs – Main Challenges

Latré et al. (2011) have mentioned that because of the typical properties of a WBAN, current protocols designed for WSNs and Ad hoc Networks are not always well suited to support a WBAN. In WSNs, maximal throughput and minimal routing overhead are considered to be more important than minimal energy consumption. Energy-efficient ad-hoc network protocols only attempt to find routes in the network that minimize energy consumption in terminals with small energy resources, thereby neglecting parameters such as the amount of operations (measurements, data processing, access to memory) and energy required to transmit and receive a useful bit over the wireless link. The authors have identified the following differences:

- The devices used in a WBAN have limited energy resources available as they have a very small form factor (often less than 1 cm^3). Furthermore, for most devices it is impossible to recharge or change the batteries although a long lifetime of the device is wanted (up to several years or even decades for implanted devices).
- All devices in a WBAN are equally important and devices are only added when they are needed for an application (no redundant devices are available).
- An extremely low transmit power per node is needed to minimize interference and to cope with health concerns in WBANs.
- In a WBAN, the propagation of the waves takes place in or on a (very) lossy medium, the human body (waves attenuated considerably).

- In a WBAN, the devices are located on the human body that can be in motion.
- High reliability and low delay is required in WBANs because the data mostly consists of medical information.
- Stringent security mechanisms are required in order to ensure the strictly private and confidential character of data through the WBAN.
- The devices in a WBAN are often very heterogeneous in terms of data rates, power consumption and reliability.
- The sensors deployed in a WBAN are under surveillance of the person carrying these devices.

2.8 Architectures Review

Several architectures for WBANs have been proposed recently in the literature. We try to summarize them in this section and later, we will make a comparison of some of them with the proposed architecture in the Chapter 6.

ETSI (European Telecommunications Standards Institution) have proposed a high-level horizontal architecture for M2M (Machine-to-Machine) systems. They divide the system into three domains: (i) the device and gateway domain where the M2M devices communicate with a gateway through short-range area networks; (ii) the network domain that connects the gateway to the applications through long-range access and core communication networks; and (iii) the application domain where various application services are defined depending on the use case. The system is depicted in the Figure 2.4 (Kartsakli et al., 2014).

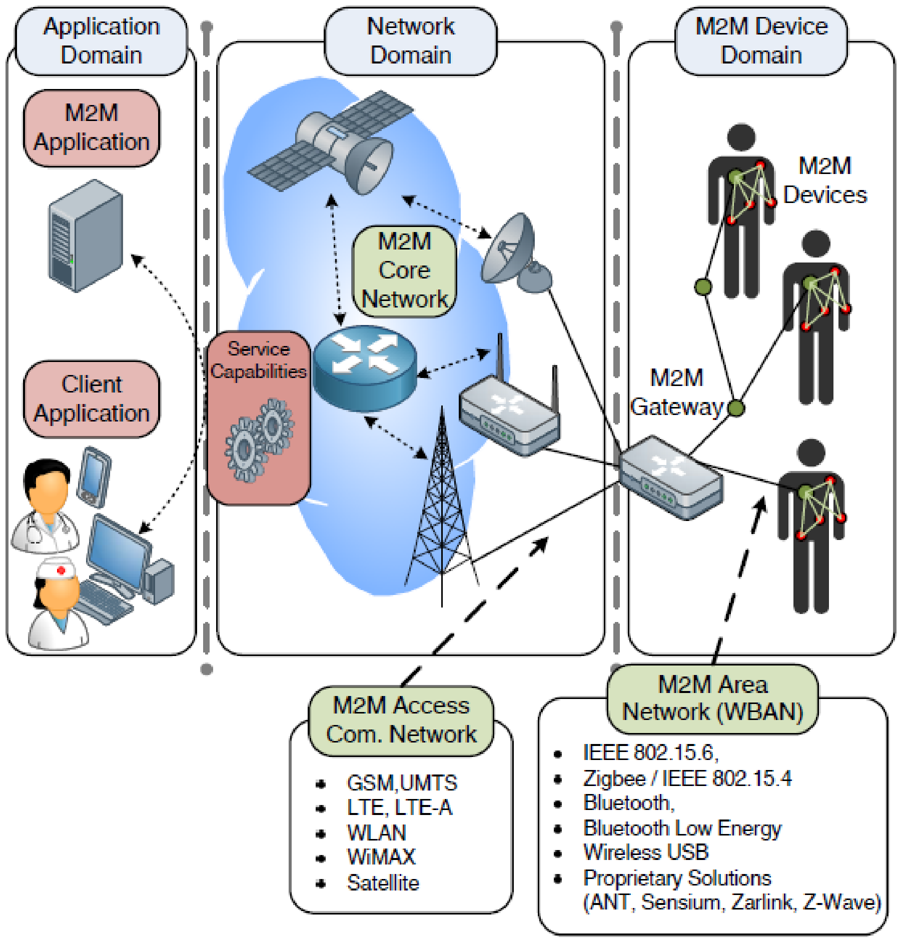

Figure 2.4. Simplified M2M architecture for wireless connectivity in mHealth scenarios

Kartsakli et al. (2014) also cite a remote monitoring scheme that provides ubiquitous connectivity for mobile patients. The Figure 2.5 depicts the scheme with a patient-attached monitoring device that collects the WBAN data, classifies them as high-priority (e.g., critical data such as blood pressure, pulse rate and heart rate) or normal priority (e.g., ECG signals) and forwards them towards the healthcare provider through a heterogeneous WiFi/WiMAX access communication network.

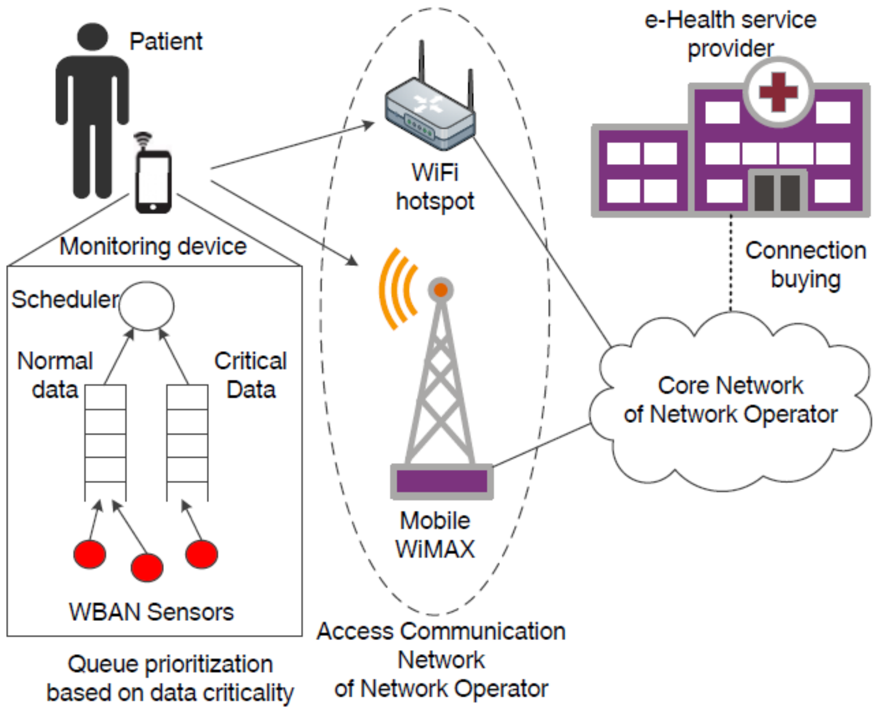

Figure 2.5. Architecture of remote patient monitoring system for WiFi/WiMAX heterogeneous scenario

Kartsakli et al. (2014) also cite a three-tier network architecture for the remote monitoring of elderly or chronic patients in their residence. The Figure 2.6 depicts the network architecture. The lower tier consists of two systems: (i) a patient-worn fabric belt, which integrates the medical sensors and is equipped with a Bluetooth transceiver; and (ii) the ambient wireless sensors that form a ZigBee network and are deployed in the patient's surroundings (e.g., in the patient's home or in a nursing house). In the middle tier, an ad hoc network of powerful mobile computing devices (e.g., laptops, PDAs, etc.) gathers the medical and ambient sensory data and forwards them to the higher tier. The middle-tier devices must have multiple network interfaces: Bluetooth and ZigBee to communicate with the lower tier and WLAN or cellular capabilities for connection with the higher layer. Finally, the higher tier is structured on the Internet and includes the application databases and servers that are accessed by the healthcare providers.

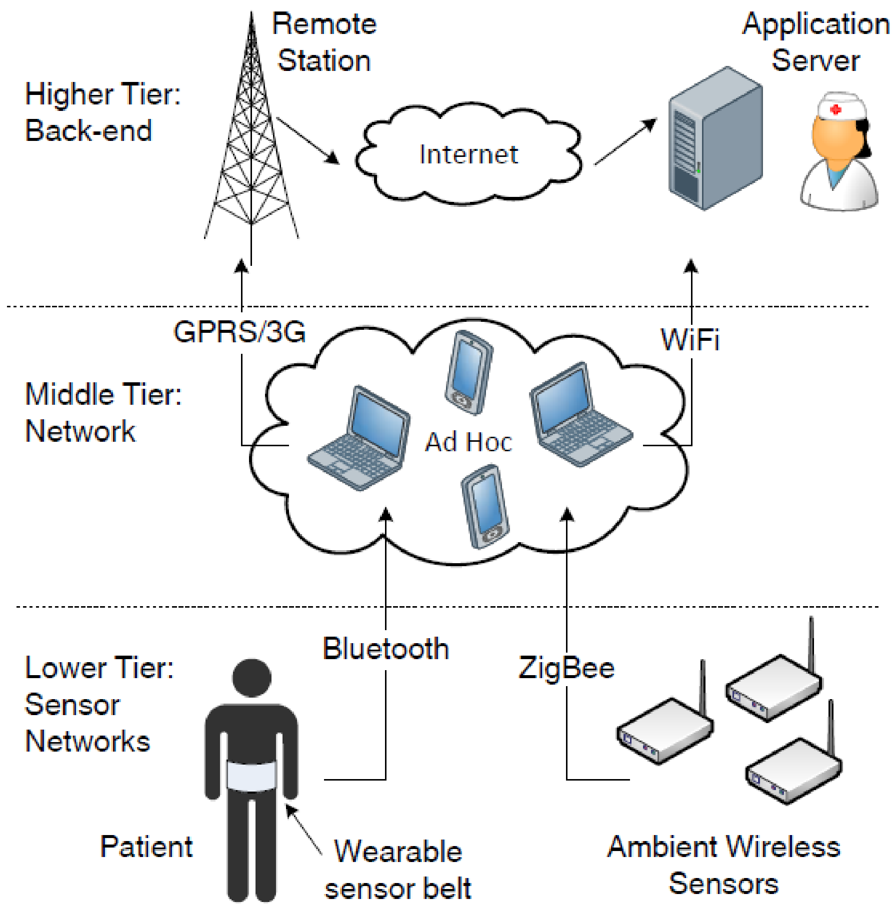

Figure 2.6. Three-tier network architecture

Kartsakli et al. (2014) also cite a system architecture based on two independent subsystems for the monitoring and location tracking of patients within hospital environments. The Figure 2.7 depicts the system architecture. The healthcare monitoring subsystem consists of smart shirts with integrated medical sensors, each equipped with a wireless IEEE 802.15.4 module. The location subsystem has two components: (i) a deployment of wireless IEEE 802.15.4 nodes that are installed in known locations within the hospital infrastructure and broadcast periodic beacon frames; and (ii) IEEE 802.15.4 end devices, held by the patients, that collect signal strength information from the received beacons. Both subsystems transmit their respective data (i.e., medical sensory data and signal strength information) to a gateway through an IEEE 802.15.4-based ad hoc distribution network.

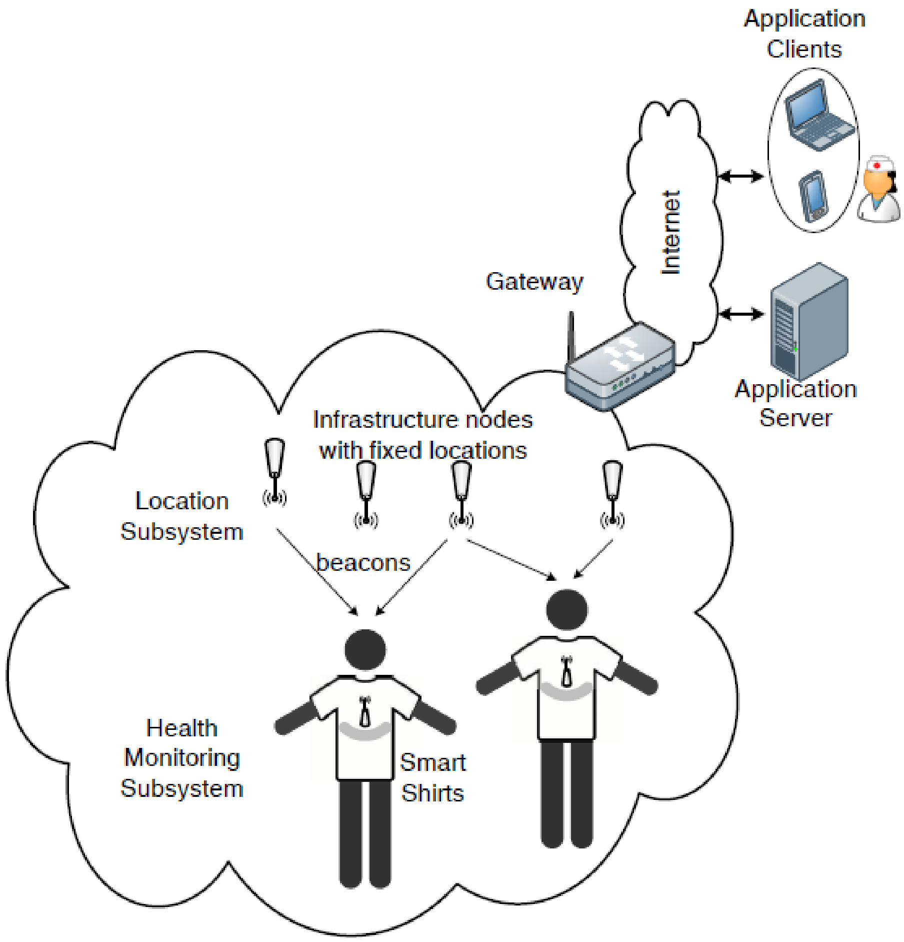

Figure 2.7. Monitoring and location tracking mHealth system architecture

A. Wang, Lin, Jin, and Xu (2016) have proposed a configurable quantized compressed sensing (QCS) architecture, in which the sampling rate and quantization configuration are jointly explored for better energy efficiency. A rapid configuration algorithm has been developed to quickly locate the optimal configuration of the sampling rate and the bit resolution, with a bound energy budget in practice, which can drastically reduce the elapsed time while keeping an excellent efficiency and capacity. The QCS architecture is depicted in the Figure 2.8.

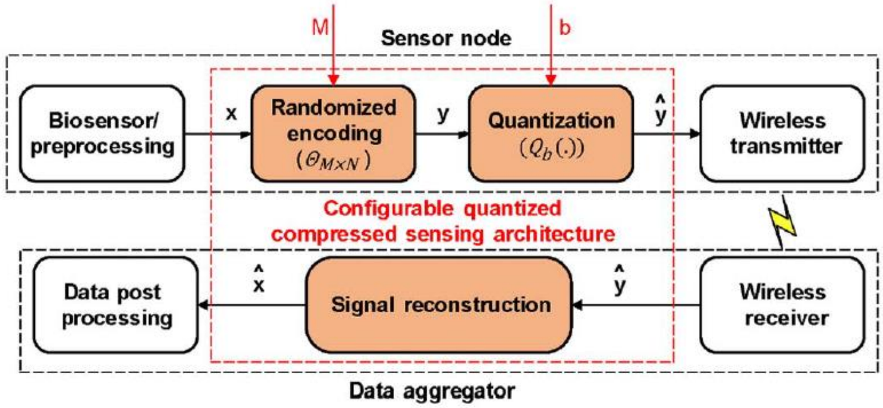

Figure 2.8. Configurable quantized CS architecture

Felisberto, Costa, Fdez-Riverola, and Pereira (2012) have proposed a WBAN architecture to recognize human movement, identify human postures and detect harmful activities in order to prevent risk situations. The architecture proposal is depicted in the Figure 2.9 and comprises five basic components: (i) Sensor node – responsible for acquiring data of inertial and physiological sensors and transmitting them to the Coordinator node; (ii) Coordinator node – responsible for serving as a forwarder of data gathered by the Sensor nodes. It forwards the data to the Gateway node or to the Mobile node and can do some kind of preprocessing before referral; (iii) Gateway node – it is the interface between the WBAN and the network that provides the Internet connection; (iv) Mobile node – an alternative interface used when the Gateway Node or Internet connection are not available; and (v) Control center – responsible for the registration and post processing of the motion events sent by the Sensor nodes.

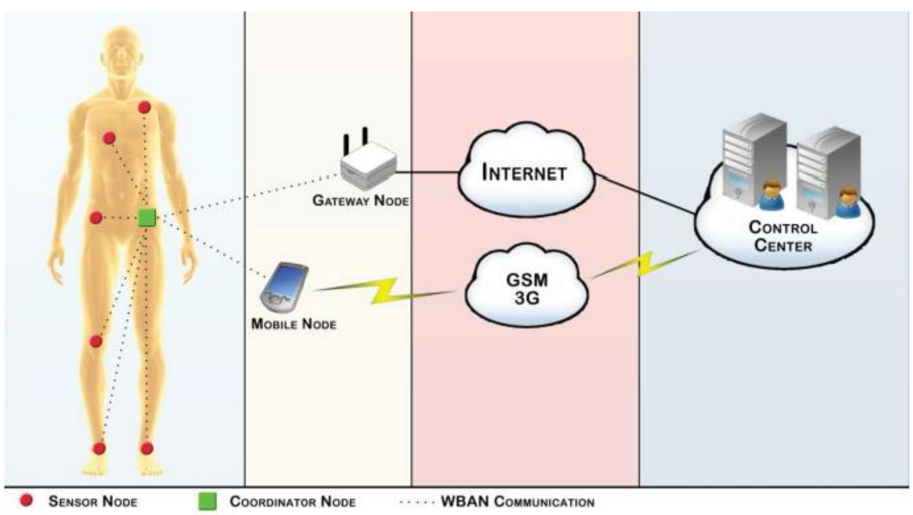

Figure 2.9. WBAN Motion Architecture

Almashaqbeh, Hayajneh, Vasilakos, and Mohd (2014) have proposed a Cloud-based real-time remote Health Monitoring System (CHMS) for tracking the health status of non-hospitalized patients while performing their daily activities. In the system, the authors' aim is to provide high QoS and to focus on connectivity-related issues between the patients and the global cloud. The CHMS design is depicted in the Figure 2.10 and includes four basic components: the wireless routers, the gateways, the users' WBANs, and the medical staff.

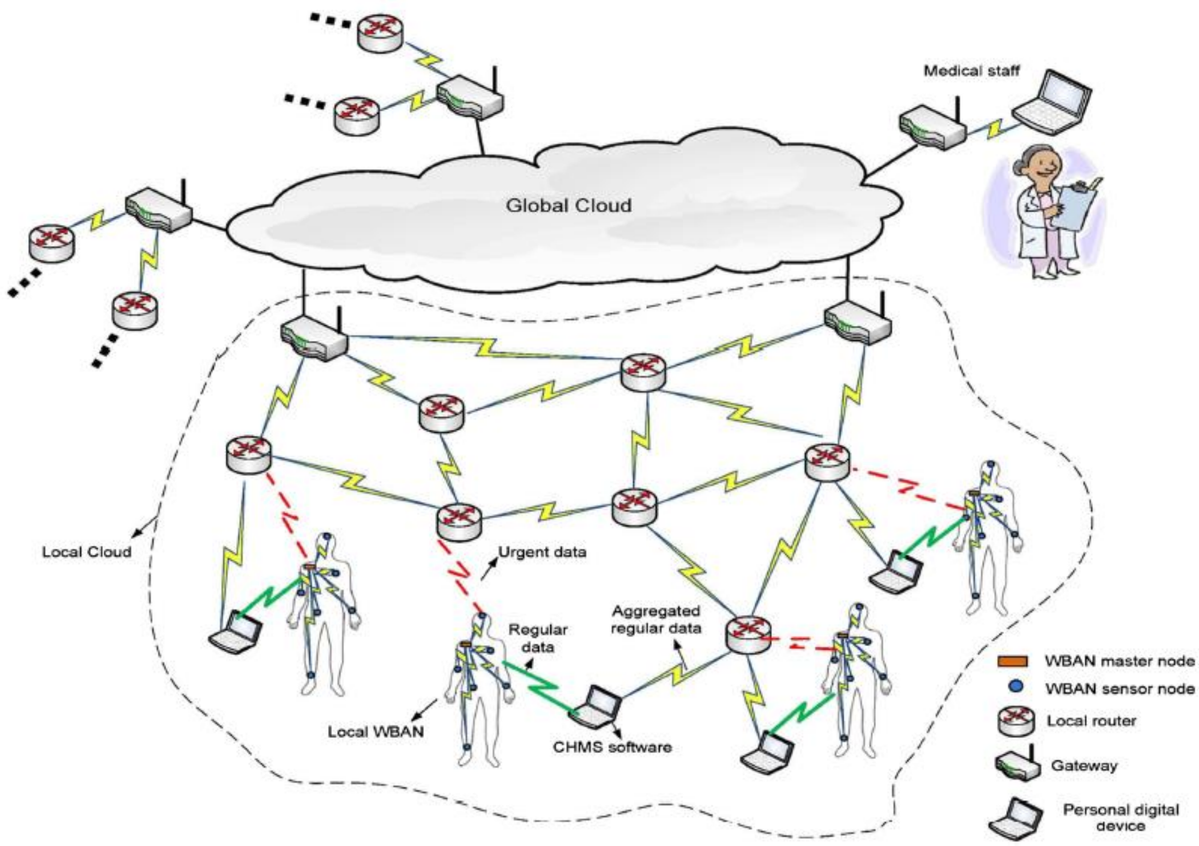

Figure 2.10. CHSM Design

Domingo (2011) has proposed a context-aware service architecture for the integration of WBANs and social networks through the IP Multimedia Subsystem (IMS). The proposed context-aware service architecture is depicted in the Figure 2.11. In this architecture, multimedia services are accessed by the user from several wireless devices via an IP or cellular network based on the vital signs monitored in a WBAN. The underlying architecture can be divided into four layers: (i) Device layer – the sensors communicate with the gateway using ultra-wideband (UWB) or the IEEE 802.15.6 standard. Bluetooth or Zigbee can be used to forward the data from the gateway to the monitoring station; (ii) Access layer – responsible for the access of the monitoring stations to the radio channel; (iii) Control layer – it controls the authentication, routing and distribution of IMS traffic; and (iv) Service layer - used to store data, execute applications, or provide services based on the data.

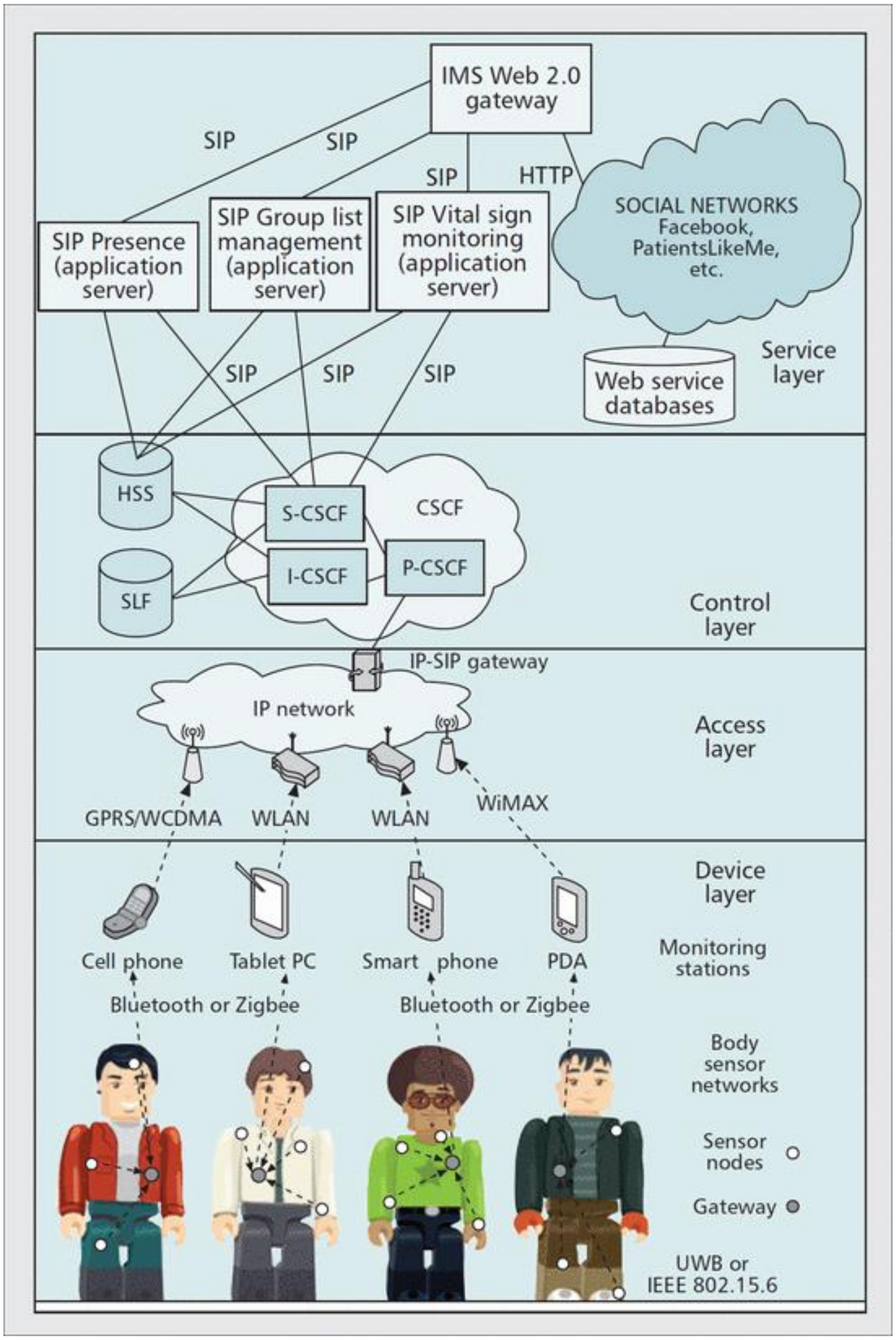

Figure 2.11. Context-aware Service Architecture

J. Wan et al. (2013) have proposed a framework for a pervasive healthcare system with Mobile Cloud Computing (MCC) capabilities. The Figure 2.12 depicts the framework. This system is composed of four main components: (i) WBANs – which collect various vital signals such as body temperature or heart rate information from wearable or implantable sensors; (ii) wired/wireless transmission; (iii) cloud services – which possess powerful VM resources such as CPU, memory, and network bandwidth in order to provide all kinds of cloud services; and (iv) users – such as hospitals, clinics, researchers, and even patients.

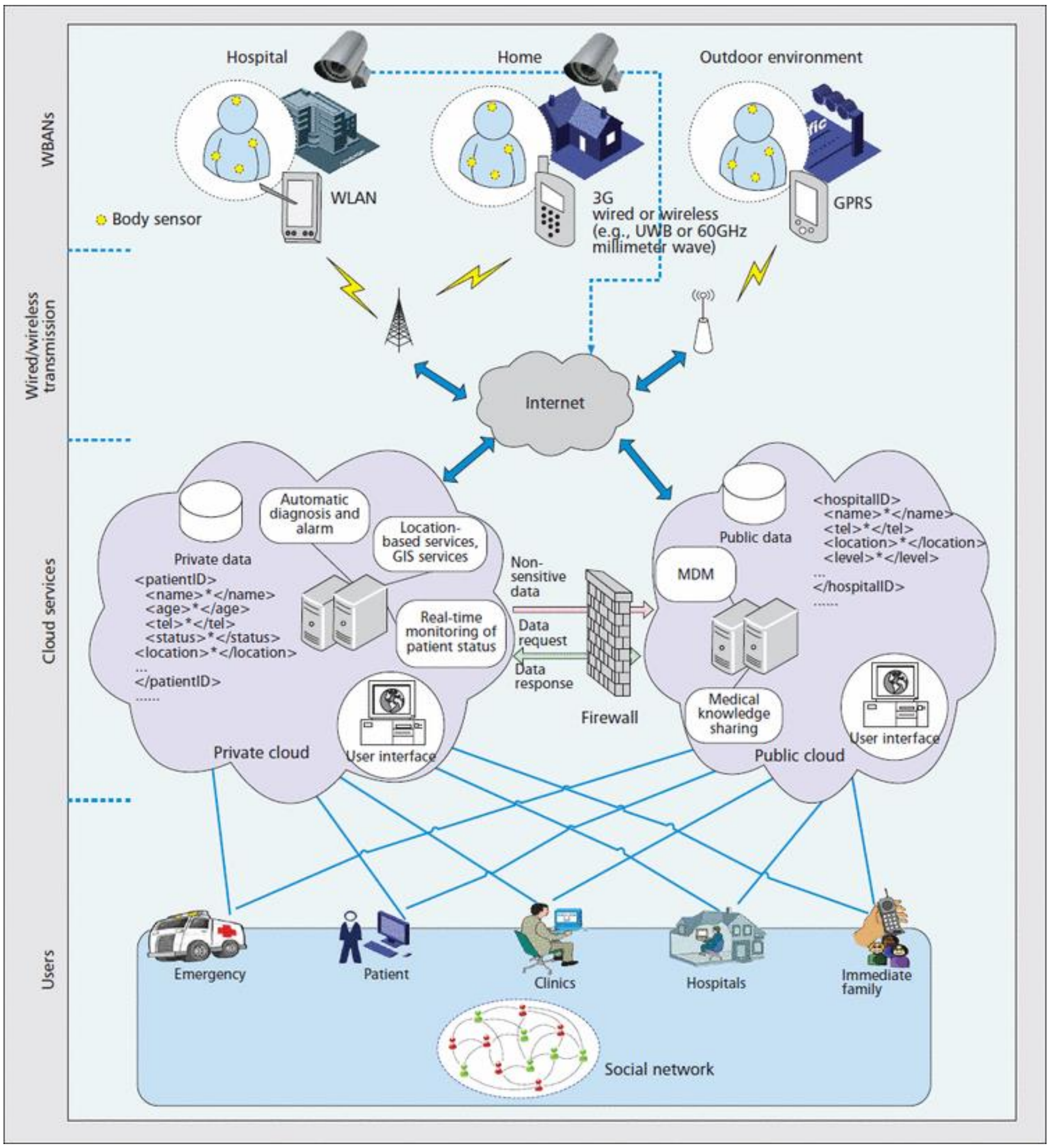

Figure 2.12. A framework for a pervasive healthcare system with MCC capabilities

CHAPTER 3 ENERGY-EFFICIENT, CONTEXT-AWARE AND RELIABLE MAC PROTOCOL FOR SPORTS WIRELESS BODY AREA NETWORKS

This chapter is divided in three main sections. The section 3.1 presents a brief of the MAC protocol proposed by the IEEE 802.15.6 Standard. The four types of access phases and the corresponding access methods proposed by the standard are mentioned. Based on the access phases of the IEEE 802.15.6 Standard MAC protocol, the section 3.2 presents an energy-efficient and emergency aware MAC protocol for WBANs. The protocol proposes three access phases and two access methods and it changes transmission schedules in order to provide quality of service for emergency traffic. Finally, the section 3.3 presents a context-aware and reliable MAC protocol for WBANs used in sports applications based on the MAC protocol proposed in the section 3.2. This last proposed MAC protocol emphasizes reliability with the improvement of the normal latency while keeping energy efficiency.

3.1 IEEE 802.15.6 MAC Protocol

In the IEEE 802.15.6 Standard, we can find four types of phases into a beacon period: (i) Exclusive Access Phase (EAP) is a time span set aside by a hub in a beacon period to transfer the traffic of the highest user priority; (ii) Random Access Phase (RAP) is a time span set aside by a hub and announced via a beacon frame for random access to the medium by the nodes in the WBAN; (iii) Managed Access Phase (MAP) is a time span set aside by a hub for improvised access, scheduled access, and unscheduled access to the medium by the hub and the nodes in the WBAN; and (iv) Contention Access Phase (CAP) is a time span set aside by a hub and announced via a preceding non-beacon frame for contention access to the medium by the nodes in the WBAN. The Figure 3.1 shows the layout of access phases in a beacon period for the MAC protocol proposed by the IEEE 802.15.6 Standard ("IEEE Standard for Local and metropolitan area networks - Part 15.6: Wireless Body Area Networks," 2012).

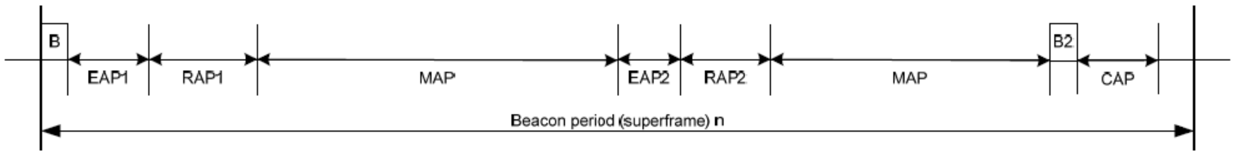

Figure 3.1. Layout of access phases in a beacon period in IEEE 802.15.6 (beacon mode)

A node or a hub shall set the Acknowledge Policy field of the MAC header of a frame to be transmitted. All the management frames have the Immediate Acknowledgment (I-Ack) policy, except for the beacon which has the Non-Acknowledgment (N-Ack) policy. All the control frames have the N-Ack policy. The data frames might have N-Ack, I-Ack, Later Block Acknowledgment policy (L-Ack) or Block Acknowledgment (B-Ack) policy.

The access method for obtaining the contended allocations can be CSMA/CA or Slotted Aloha access. A hub or a node may obtain contended allocations in EAP1 and EAP2, only if it needs to send data type frames of the highest user priority. The hub may obtain such a contended allocation pSIFS (Priority Short Inter-Frame Space) after the start of EAP1 or EAP2 without actually performing the CSMA/CA or slotted Aloha access procedure. Only nodes may obtain contended allocations in RAP1, RAP2, and CAP, to send management or data type frames. The Table 3.1 shows the values for the contention window bounds for CSMA/CA protocol and the contention probability thresholds for the Slotted Aloha access protocol.

Table 3.1. Contention window for CSMA/CA and contention probability for slotted Aloha

	CSMA/CA		**Slotted Aloha access**	
User Priority	**CWmin**	**CWmax**	**CPmax**	**CPmin**
0	16	64	1/8	1/16
1	16	32	1/8	3/32
2	8	32	1/4	3/32
3	8	16	1/4	1/8
4	4	16	3/8	1/8
5	4	8	3/8	3/16
6	2	8	1/2	3/16
7	1	4	1	1/4

In the MAP phase, the hub may arrange scheduled uplink allocation intervals, scheduled downlink allocation intervals, and scheduled bilink allocation intervals; provide unscheduled bilink allocation intervals; and improvise type-I, but not type-II, immediate polled allocation intervals and posted allocation intervals. Scheduled allocations may be 1-periodic or m-periodic allocations, except that a node cannot have both 1-periodic and m-periodic allocations in the same WBAN. To have a 1-periodic allocation, which has one or more allocation intervals spanning the same allocation slots in every beacon period, a node shall treat all beacon periods as its wakeup beacon periods. To have an m-periodic allocation, which has one or more allocation intervals spanning the same allocation slots in every $m > 1$ beacon periods, a node shall treat the beacon periods containing its allocation intervals as its wakeup beacon periods ("IEEE Standard for Local and metropolitan area networks - Part 15.6: Wireless Body Area Networks," 2012).

3.2 Energy Efficiency and Emergency Awareness

We can identify three traffic types in a sports WBAN: (i) Normal traffic which is the set of packets sent by nodes with a frequency pre-established when they connected to the WBAN; (ii) On-demand traffic which is the set of packets sent by nodes as an answer to the requests made by the hub at any moment (especially after an emergency event) and (iii) Emergency traffic which is the set of packets generated by all kinds of alerts like medical emergency alerts, low battery alerts or buffer alerts from the nodes (see Table 3.2).

Table 3.2. Traffic Types in a Sports WBAN

Type	**Description**
Normal	Periodic packets from the nodes to the hub
On-Demand	Packets from the nodes to the hub after a poll
Emergency	Packets with alerts from the nodes to the hub

A beacon is our synchronization event. Nodes update their timers each time they receive a beacon. A beacon contains information about the beacon period length, the allocation slot length, MEP (Management and Emergency Phase) length, SRP (Slot Reallocation Phase) length and the RIB (Reallocation Indicator Bit). Nodes go back to a default slot allocation when they receive a beacon with the RIB equal to 0 (zero), then they go to sleep mode until their own slot allocation in MAP starts. The default slot allocation is the one they received when they listened to the first connection assignment. If the RIB is equal to 1 (one), nodes go to listening mode during SRP.

3.2.1 Preliminary Proposed Phases in the Beacon Period

We use the same MAP phase as IEEE 802.15.6 Standard for contention-free transmission and we propose two new phases for the beacon period: Slot Reallocation Phase (SRP) and Management and Emergency Phase (MEP). (i) SRP allows the hub to send slot reallocations when it has received packets with emergency alerts during MAP and MEP phases. The hub uses the TDMA protocol and assigns itself all the slots in SRP. In this way, the hub avoids contention and packet collisions during SRP. (ii) MEP allows nodes to send connection requests when they are unconnected (e.g. when they are turned on for the first time or they have lost the connection to the WBAN) and to transmit packets with emergency alerts when they were not able to do it while their own assigned slots in MAP. Nodes use CSMA/CA protocol for contention-based transmission during MEP. Figure 3.2 depicts the three proposed phases for each beacon period with the protocols used for transmission. The phase called B corresponds to the Beacon listening.

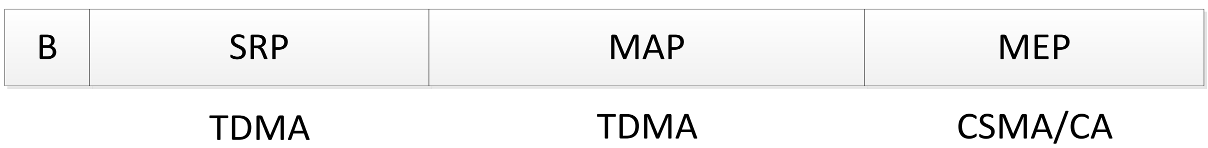

Figure 3.2. Phases in a beacon period for the proposed MAC Protocol

3.2.1.1 Slot Reallocation Phase (SRP)

For transmission during SRP, the hub must send an alert (Reallocation Indicator Bit) into the beacon for the current beacon period, indicating the reallocation for all nodes. The hub uses all slots in SRP to transmit the new schedule in MAP for each node. In this way, the hub avoids contention with the nodes and packet collisions. Each node receives the new slot allocation for the next MAP and sends an I-Ack.

3.2.1.2 Managed Access Phase (MAP)

For transmission during MAP, each node uses the slots assigned when it connected to the WBAN for the first time (if the beacon for this beacon period had the RIB equal to 0) or the slots assigned during SRP (if the beacon for this beacon period had the RIB equal to 1). Nodes transmit normal traffic and give the highest priority to emergency traffic each time they arrive, sending each emergency packet before the remaining normal traffic. If needed, nodes can request for the free slots at the end of MAP to send additional emergency traffic.

3.2.1.3 Management and Emergency Phase (MEP)

For transmitting during MEP, nodes use CSMA/CA protocol which makes periodic checks in the channel. The only way of failing due to repeated busy signals is to eventually not fit in the current MEP. If the maximum number of retransmissions for a packet is reached, the packet is deleted and it is counted as lost. Since we are using CSMA/CA for transmission, we double the Contention Window (CW) after every second fail.

3.2.2 Preliminary Nodes States

After the beacon reception, a node must decide whether it goes to sleep mode or it goes to reception mode for listening to the slot reallocations sent by the hub during SRP. In the next phase MAP, the node goes to sleep mode if it does not have the first slot assigned for transmission, then, it wakes up and goes to transmission mode when its assigned slots begin. After the final assigned slot for transmission in MAP, the node goes to sleep mode and it wakes up in MEP for transmitting additional emergency packets or connection requests (when it is unconnected). After finishing transmission in MEP, nodes go to sleep mode until they wake up for listening to the next beacon. The Figure 3.3 depicts the node states for the MAC protocol during the three proposed phases.

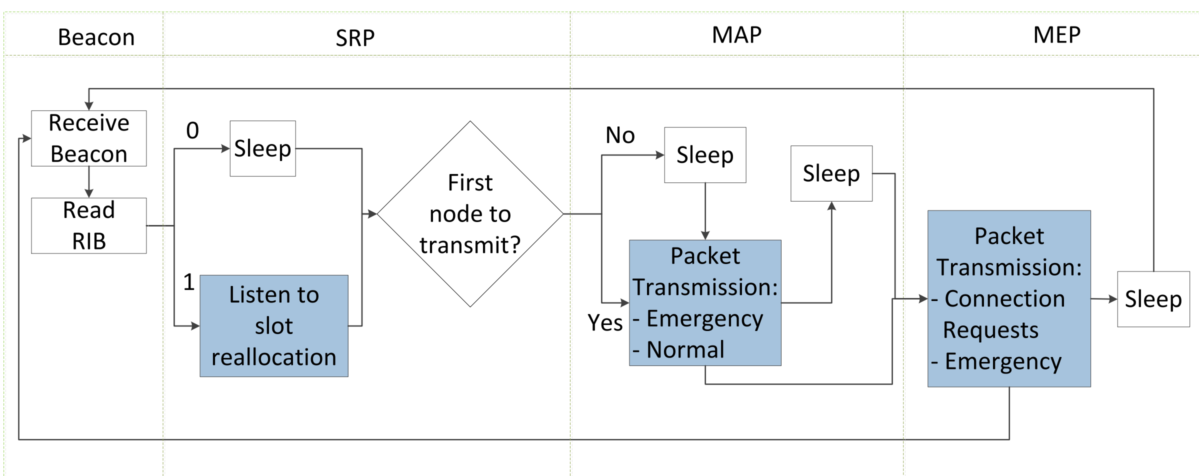

Figure 3.3. Node states for the proposed MAC protocol

3.2.3 Preliminary Hub States

After sending a beacon, the hub can go to idle mode (the hub never sleeps) if the RIB in the sent beacon was 0 (zero). The hub must transmit the slot reallocations for each node if the RIB was 1 (one). After transmission during SRP, the hub goes to idle mode in SRP and then, it starts to listen to packets during MAP. During MEP, it listens to connection requests from unconnected nodes and emergency packets, and it transmits connection assignments. Finally, the hub goes to idle mode until the time of sending a new beacon for starting a new beacon period. The Figure 3.4 depicts the hub states for the MAC protocol during the three proposed phases.

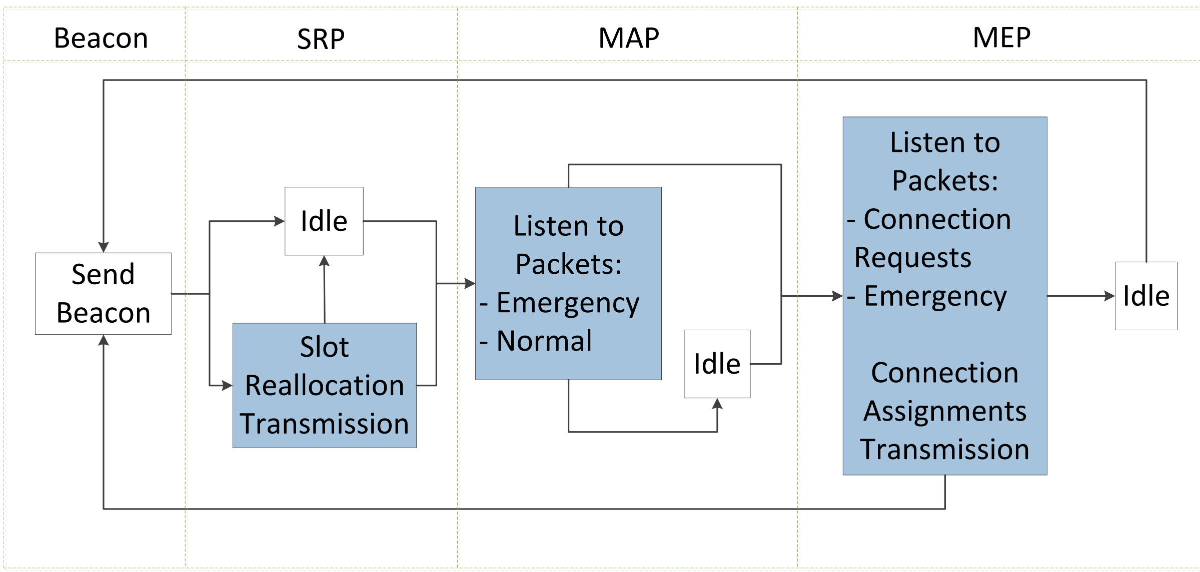

Figure 3.4. Hub states for the proposed MAC protocol

3.2.4 Preliminary Slot Reallocation Technique

We use two extra bits into each packet in the Application layer for indicating the emergency type. The Table 3.3 shows the emergency types in the application layer. Normal packets have both bits with a value of 0 (zero) indicating that there is no alert for the current packet. When the first bit has value of 0 (zero) and the second bit has a value of 1 (one), this means a High Buffer Level, indicating in advance that the sensor node is going to collect a lot of data and it is going to need more assigned slots during MAP for the next beacon period. This alert is very useful for avoiding buffer overflow. When both bits (first and second) have a value of 1 (one), this means Emergency Data, indicating a packet of the maximum priority that needs to be sent immediately during either MAP or MEP phases.

Table 3.3. Emergency type in the Application layer

First Bit	Second Bit	Emergency Type
0	0	Normal
0	1	High Buffer Level
1	1	Emergency Data

We use Immediate Acknowledge (I-Ack) Policy for all data packets rather than using of Later Acknowledge (L-Ack) or Block Acknowledge (B-Ack) policies proposed by the IEEE 802.15.6 Standard. Uplink requests are simplified to only ask for the number of slots needed (always two for our proposed MAC protocol). Emergency packets have their own buffer, and are handled with higher priority than normal packets during MAP. Management packets that need to be acknowledged, have their own buffer, and are handled with higher priority than Emergency packets during MEP.

3.2.5 Preliminary Experimental Results

3.2.5.1 Preliminary Simulation Parameters

The simulated network was composed of ten nodes: nine sensor nodes and one hub. The sensor in the center is the hub and we assumed it never goes to sleep mode (it goes only to idle mode). The Figure 3.5 shows the star topology for the simulation scenario.

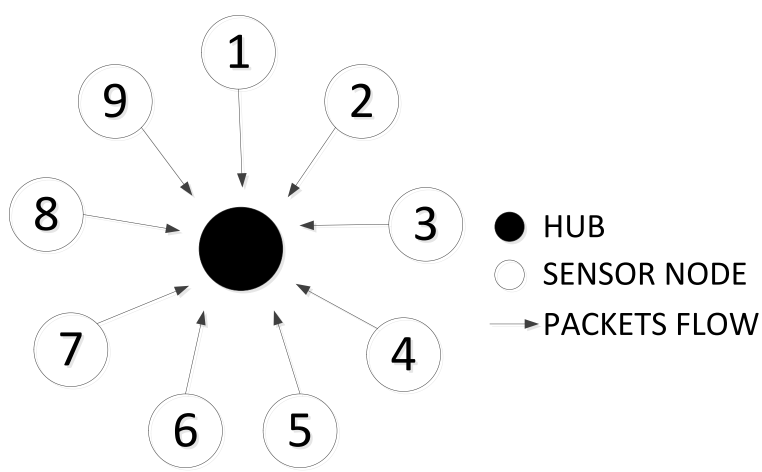

Figure 3.5. Star topology for the simulation scenario of the proposed MAC protocol

The simulation time was 3000s (50 min). The additional simulation parameters for MAC and physical layers used for the simulation scenario are listed in the Table 3.4. The beacon period length was 32 slots for both the IEEE 802.15.6 Standard and the proposed MAC protocol. The

MAP length was 26 slots for both the IEEE 802.15.6 Standard and the proposed MAC protocol. The remaining six slots were distributed between EAP (three slots) and RAP (three slots) phases for the IEEE 802.15.6 Standard, and between SRP (three slots) and MEP (three slots) phases for the proposed MAC protocol. The values for the parameters: allocation slot length, scheduled access length, scheduled access period, and contention slot length were the same for both protocols in order to keep fairness in the comparison.

Table 3.4. Simulation Parameters for the proposed MAC Protocol

Layer	Parameter	Value
MAC	Allocation Slot Length (ms)	10
	Beacon Period Length (slots)	32
	SRP Length (slots)	3
	MAP Length (slots)	26
	MEP Length (slots)	3
	Scheduled Access Length (slots)	2
	Scheduled Access Period	1
	Contention Slot Length (ms)	0.36
Physical	Hubs	1
	Sensors	9
	Topology	Star
	TX Output Power (dBm)	-10
	Baseline Node Power (mW)	10

3.2.5.2 Preliminary Simulation Results

The simulations were made for comparing the proposed MAC protocol with the IEEE 802.15.6 standard MAC protocol. Two variables were modified for the simulations: the percentage of emergency probability in each node and the total number of nodes in the WBAN. An emergency probability of 0.001 means that each time a node is going to send a packet, there is a probability of 0.001% to be an emergency packet and 99.999% to be a normal packet.

The first parameter used for the comparison of the proposed MAC protocol against the IEEE 802.15.6 MAC protocol was the average energy consumption. The emergency probability in the sensor nodes was varied, and the average energy consumption in the whole WBAN was evaluated. The energy consumption (in milliwatts) when each node has a given probability to generate emergency packets is depicted in the Figure 3.6. The average energy consumption of the proposed MAC protocol was lower than the IEEE 802.15.6 MAC protocol because the sensor nodes do not spend a lot of energy in contention-based transmission, as IEEE 802.15.6 does during RAP and EAP phases. The proposed MAC protocol only uses contention-based transmission during the MEP phase and it decreases packet collision which is one of the most important sources of energy wasting in WBANs. There is an average difference of almost 800 microwatts between the IEEE 802.15.6 MAC protocol and the proposed MAC protocol. This difference represents an improvement in the energy efficiency of almost 2.5%. This improvement in the energy consumption is very significant when we see the good behavior of the proposed MAC protocol with the percentage of emergency packet loss in the Figure 3.7. A low number of lost emergency packets combined with a low energy consumption suggest a very good energy effectiveness of the solution for the WBAN.

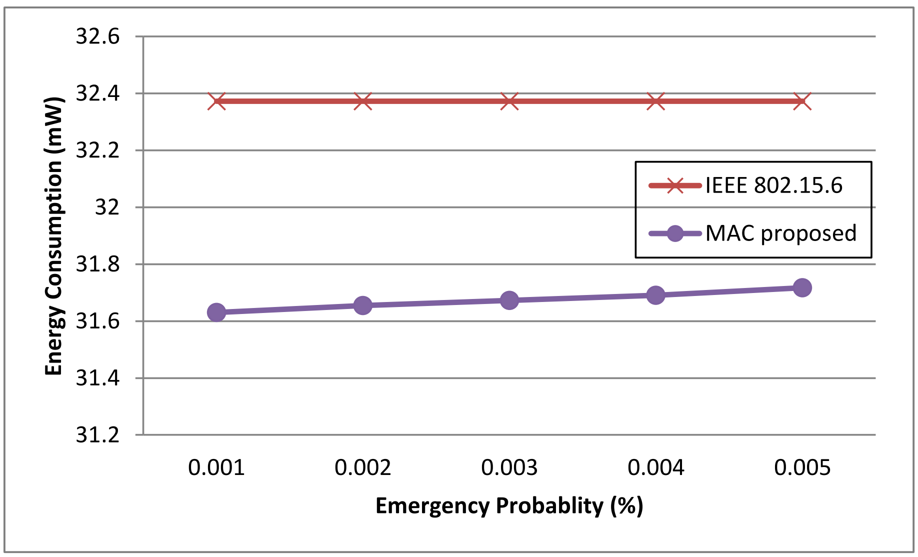

Figure 3.6. Energy consumption vs Emergency probability

The second parameter used for the comparison of the proposed MAC protocol against the IEEE 802.15.6 MAC protocol was the percentage of emergency packet loss. The Figure 3.7 depicts the percentage of emergency packet loss when each node has a given probability to generate emergency packets. The emergency packet loss shown by the proposed MAC protocol was always less than 0.8% for all the given emergency probabilities, while the IEEE 802.15.6 MAC protocol always showed more than 31% of emergency packet loss. The excellent performance of emergency packet loss in the proposed MAC protocol is due to the emergency awareness provided by the protocol. Each time an emergency is detected, the emergency node is assigned the first slots in the MAP phase. Each node can also request more slots in the ending of the MAP phase if available. Besides, the MEP phase is dedicated only to management traffic for connection and to additional emergency traffic. This improvement suggests a trade-off with the percentage of normal packet loss due to buffer overflow. If a node with an emergency event has a lot of buffered normal traffic, these normal packets could be lost due to buffer overflow because the emergency traffic has the highest priority for transmission during the MAP and the MEP phases in the proposed MAC protocol. The buffered normal traffic has to wait until the next MAP phase in the next beacon period in order to be transmitted.

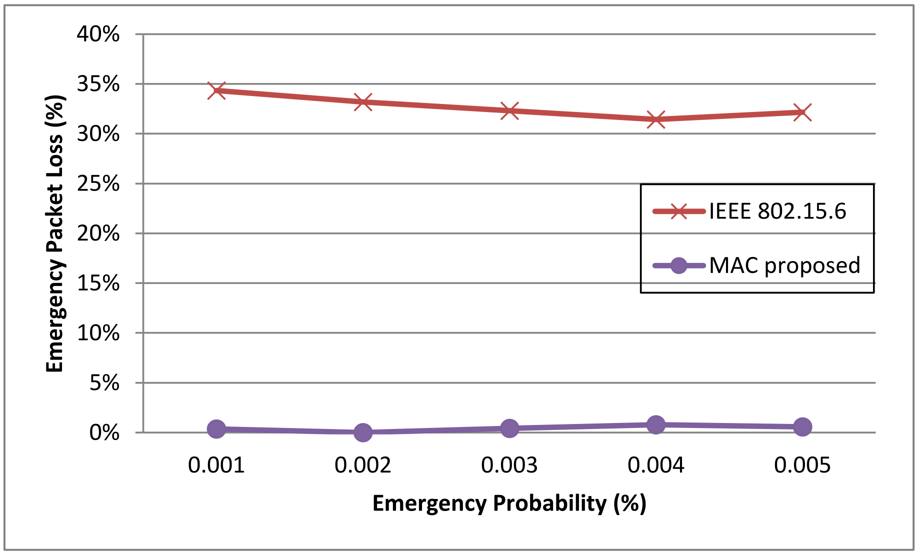

Figure 3.7. Emergency packet loss vs Emergency probability

The third parameter used for the comparison of the proposed MAC protocol against the IEEE 802.15.6 MAC protocol was the latency distribution. The distribution of latency for emergency traffic is depicted in Figure 3.8. The emergency data probability used for this simulation was 0.001% and the total number of nodes was 10 ten. The number of emergency packets with low latency (0-120 ms) in the proposed MAC protocol was much higher than the IEEE 802.15.6 MAC protocol because the emergency traffic has more priority than the normal traffic during the MAP phase and the emergency nodes are assigned the first slots during MAP. Besides, there is a contention phase, the MEP phase, especially dedicated to both management and additional emergency packets within each beacon period. This improvement implies the lowest latency for emergency traffic at the cost of higher latency for normal traffic when an emergency event happens at any node. The normal traffic into a node has to wait until the next MAP phase in the next beacon period in order to be transmitted, when an emergency event happens in that node.

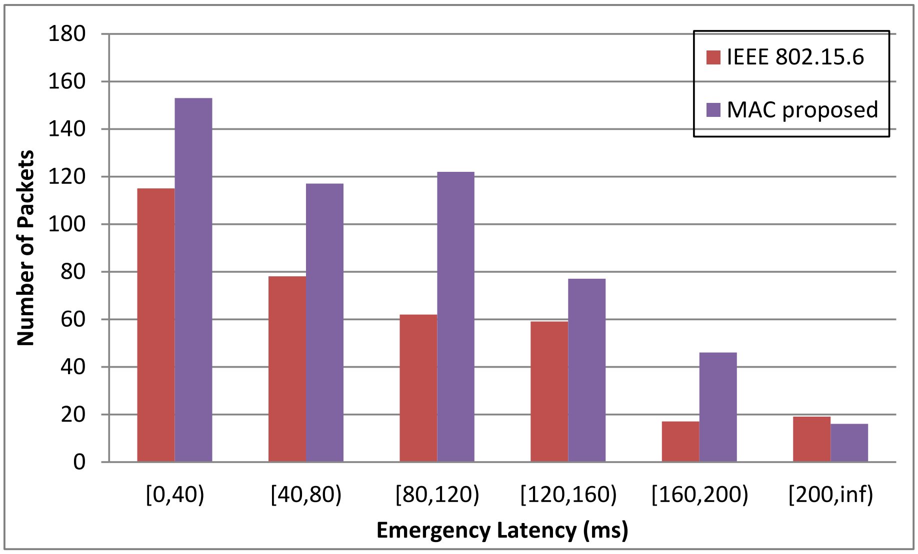

Figure 3.8. Latency for emergency traffic

The distribution of latency for normal traffic is depicted in the Figure 3.9. The emergency data probability used for this simulation was 0.001% and the total number of nodes was 10 ten. The number of normal packets with high latency in the proposed MAC protocol was much higher than the IEEE 802.15.6 MAC protocol because the emergency traffic has more priority than the normal traffic during the MAP phase. After an emergency event happens in any node, the emergency node is assigned the first slots in MAP phase to transmit the emergency packets. If the emergency event produces a lot of emergency traffic, then, the node can request more slots at the end of the MAP phase. The emergency node can also send additional emergency traffic during the MEP phase. This improvement implies the lowest latency for emergency traffic at the cost of higher latency for normal traffic when an emergency event happens at any node. The normal traffic into a node has to wait until the next MAP phase in the next beacon period in order to be transmitted, when an emergency event happens in that node. This is the reason for the high number of normal packets with the latency of 200 ms or more.

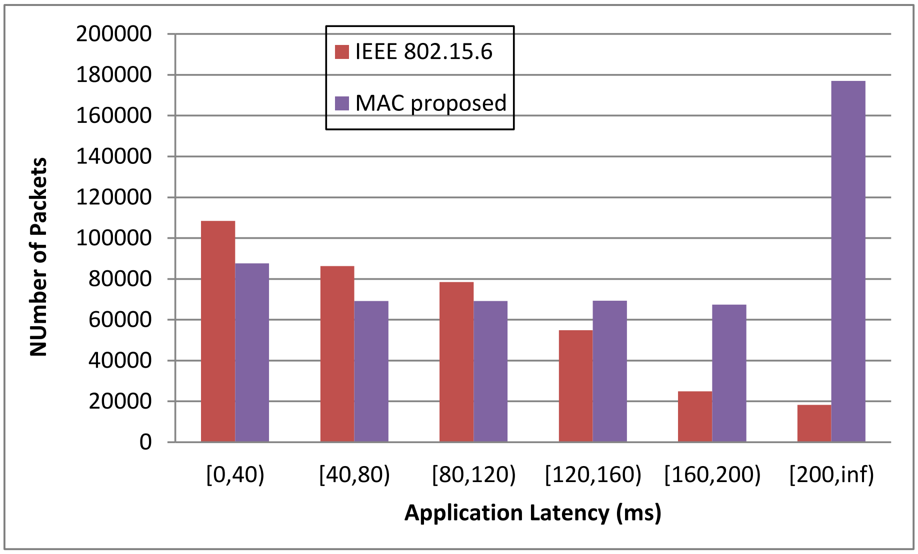

Figure 3.9. Latency for normal traffic

For the last two simulations, the total number of nodes was modified from two to twelve. The Figure 3.10 depicts the percentage of emergency packet loss with a given number of nodes in the WBAN. We started the simulations with two nodes: the hub and one sensor node. We added two additional nodes until we reached twelve nodes: the hub and eleven sensor nodes. The percentage of emergency packet loss in the proposed MAC protocol was much less (lower than 0.5%) than the IEEE 802.15.6 MAC protocol because the nodes can send a lot of emergency packets pending MAP and send the remaining emergency traffic pending MEP with no need of contention and competition with normal traffic (periodic packets). Both protocols showed 0% of emergency packet loss when the WBAN had only two nodes (the hub and one sensor node). The proposed MAC protocol also showed 0% of emergency packet loss with four and six nodes, while the IEEE 802.15.6 MAC protocol showed 19% and 29% respectively. As the number of nodes increases, the percentage of emergency packet loss in the proposed MAC protocol keeps almost the value of zero, but at the cost of an increase in the percentage of normal packet loss. The proposed MAC protocol is emergency-aware and we need to consider a trade-off with the normal traffic behavior when an emergency event happens at any node. When the WBAN is composed of 10 or 12 nodes, the IEEE 802.15.6 showed an emergency packet loss higher than 30% which is too much for emergency events in a WBAN.

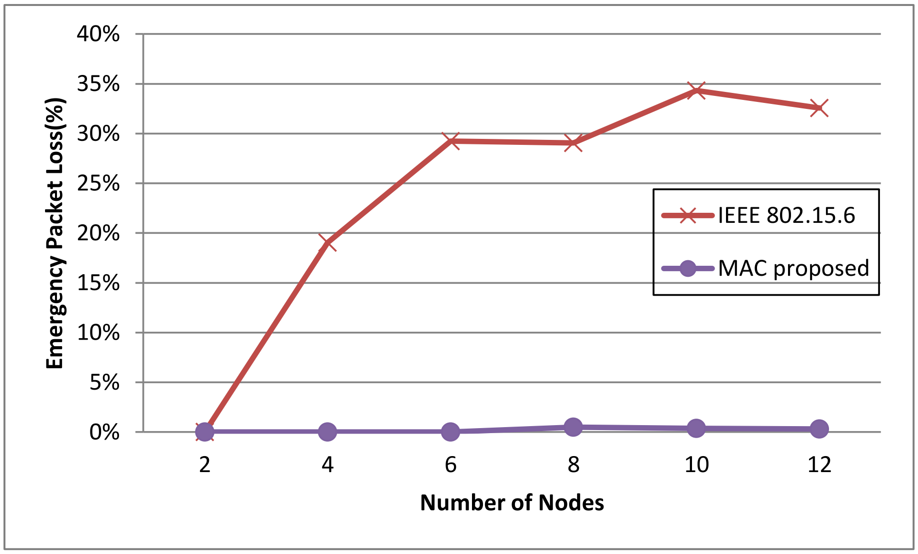

Figure 3.10. Emergency packet loss vs. Number of nodes

The Figure 3.11 depicts the average energy consumption (in milliwatts) with a given number of nodes in the WBAN. Again, we started the simulations with two nodes: the hub and one sensor node. We added two additional nodes until we reached twelve nodes: the hub and eleven sensor nodes. The average energy consumption in the proposed MAC protocol was fewer than the IEEE 802.15.6 MAC protocol because the nodes do not spend a lot of energy in contention-based transmission avoiding the packet collisions which is one of the most important sources of energy wasting. Even with only two nodes (the hub and one sensor node), the proposed MAC protocol outperformed the IEEE 802.15.6 MAC protocol with an energy efficiency of 1.19%. This difference grows up according as the number of nodes increases, because the contention is higher. The average improvement of energy efficiency is almost 2%. With the increase of the number of nodes, the average energy consumption in the WBAN decreases because each node needs to wait more in order to transmit normal and emergency traffic during the MAP phase and additional emergency traffic during the MEP phase. This behavior allows the node to avoid packet collisions during the contention phase and energy wasting through overhearing and idle listening.

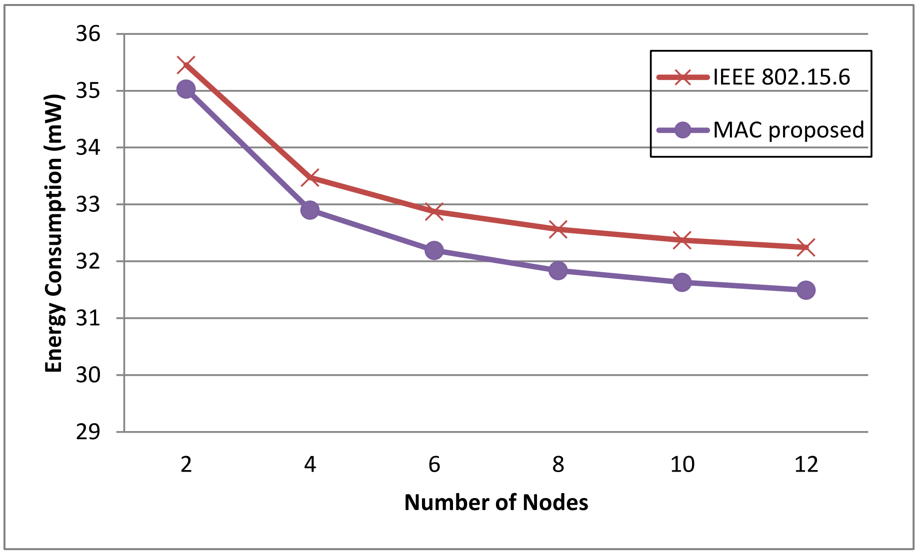

Figure 3.11. Energy consumption vs. Number of nodes

3.3 Context Awareness and Reliability

This section presents the improvement of the normal latency without the impairing of the emergency latency and the energy consumption, as well as the appropriate adjustment to the Slot Reallocation Technique of the MAC protocol proposed in the previous section. This new proposed MAC protocol for sports applications is called SportsBAN. The protocol is context-aware and offers reliability to the whole WBAN. The main difference with the proposed MAC protocol in the previous section is that this new protocol allows the transmission of normal traffic in the last contention-based phase.

3.3.1 Final Proposed Phases in the Beacon Period

The same MAP phase as IEEE 802.15.6 Standard is used in the proposed MAC protocol and two different phases instead of RAP and EAP are proposed. The proposed phases for each beacon period are: (i) Slot Reallocation Phase (SRP) that allows the hub to send slot reallocations when it has received packets with emergency alerts. The hub uses the TDMA protocol, assigning itself all the slots during SRP and being the only node that transmits; and (ii) Special Contention Access Phase (SCAP) that allows nodes to send connection requests when they are unconnected (e.g. when they are just turned on or they have lost the connection with the WBAN) and to transmit additional packets (emergency and normal) when they were not able to do it while their own assigned slots during MAP. The nodes use CSMA/CA protocol for contention-based transmission during SCAP. The Figure 3.12 depicts the four proposed phases for each beacon period.

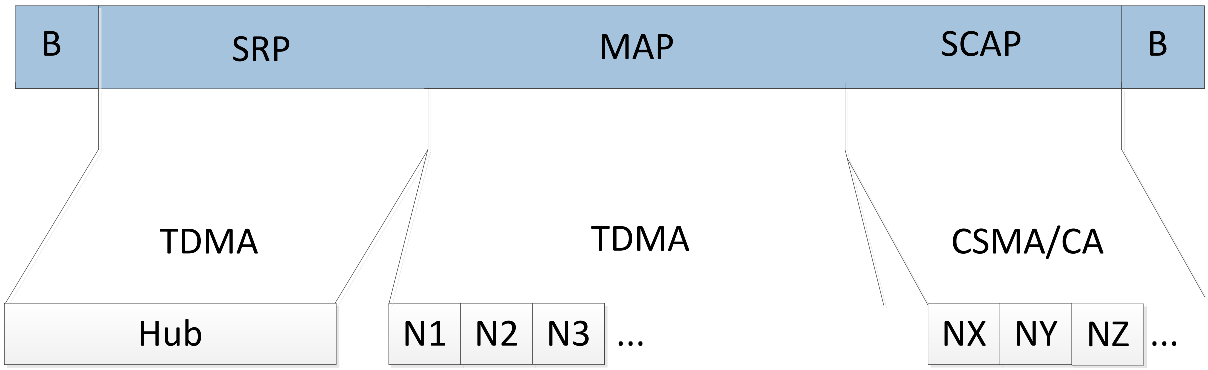

Figure 3.12. Phases for each beacon period in SportsBAN

3.3.1.1 Beacon Reception

The beacon is the synchronization event. The nodes update their timers each time they receive a beacon. A beacon contains information about beacon period length, allocation slot length, SRP length, SCAP length and the Reallocation Indicator Bit (RIB). When RIB is one, nodes go to the listening mode during SRP. When RIB is zero, nodes go to the sleep mode during SRP and during MAP until their own slot allocation in MAP starts.

3.3.1.2 Slot Reallocation Phase

For transmitting during SRP, the hub must send an alert into the beacon indicating for this beacon period a slot reallocation for all nodes. The transmission is made using TDMA protocol, where all slots are assigned to and used by the hub for transmitting the new slot allocations for all nodes.

3.3.1.3 Managed Access Phase

For transmitting during MAP, each node uses the slots assigned when it connects for the first time to the WBAN or the slots assigned during SRP (if the beacon for this beacon period set the RIB to one). The nodes transmit normal traffic and give the highest priority to emergency packets each time they arrive, sending each emergency packet before the remaining normal traffic during MAP.

3.3.1.4 Special Contention Access Phase

For transmitting during SCAP, the nodes use CSMA/CA protocol that makes periodic checks in the channel before transmitting. Each time the channel is busy, the time shown in the expression (3.1) is used arbitrarily for the next check. This allows to decrease the probability of a busy channel when the checks are made continuously.

$$T_{next\_check} = 3 \times CS_{length} \tag{3.1}$$

Where CS_{length} is the contention slot length. The only way of failing due to repeated busy signals is to eventually not fit in the current SCAP. If the maximum number of retransmissions for a packet is reached, the packet is deleted and it is counted as lost. Since CSMA/CA is used for the contention-based transmission, the contention window is doubled after every second fail. The normal and emergency packets are sent during SCAP, but giving more priority to emergency traffic. When the node is unconnected, the management packets have the highest priority during SCAP.

3.3.2 Final Node States

The Figure 3.13 depicts the node states for the proposed MAC protocol during the four phases in the beacon period. After the beacon reception, a node reads the RIB and either goes to the sleep mode or goes to the reception mode for listening to the slot reallocations sent by the hub during SRP. In MAP, the node goes to the sleep mode if it does not have the first slot assigned for transmission, then, it wakes up and goes to the transmission mode. After the final slot assigned for transmission in MAP, the node goes to the sleep mode and it wakes up in SCAP for transmitting more connection requests (if it is still unconnected) and emergency and normal packets. After finishing transmission in SCAP, the nodes go to the sleep mode until they wake up for listening to the next beacon.

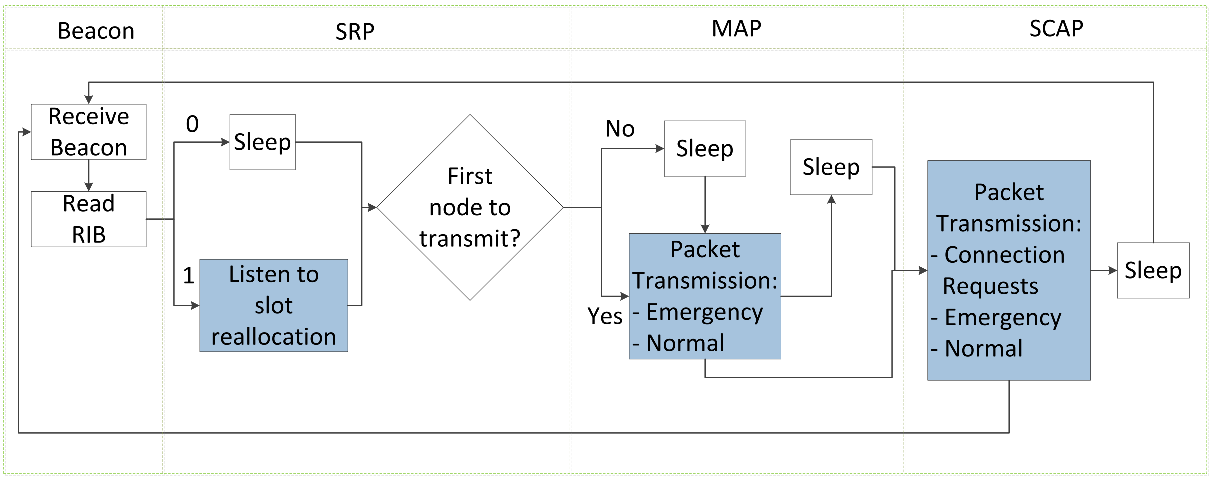

Figure 3.13. Node states in SportsBAN

3.3.3 Final Hub States

The Figure 3.14 depicts the hub states for the proposed MAC protocol during the four phases in the beacon period. After sending a beacon, the hub can go to idle mode (it never sleeps) if the RIB in the beacon was zero or it can transmit all the slot reallocations for each node if the RIB was one. After transmission during SRP, the hub goes to the idle mode in SRP and then, it starts to listen to emergency and normal packets in MAP. In SCAP, it listens to connection requests (from unconnected nodes) and emergency and normal traffic. It transmits connection assignments to unconnected nodes. Finally, the hub goes to the idle mode until the time of sending a new beacon for starting a new beacon period.

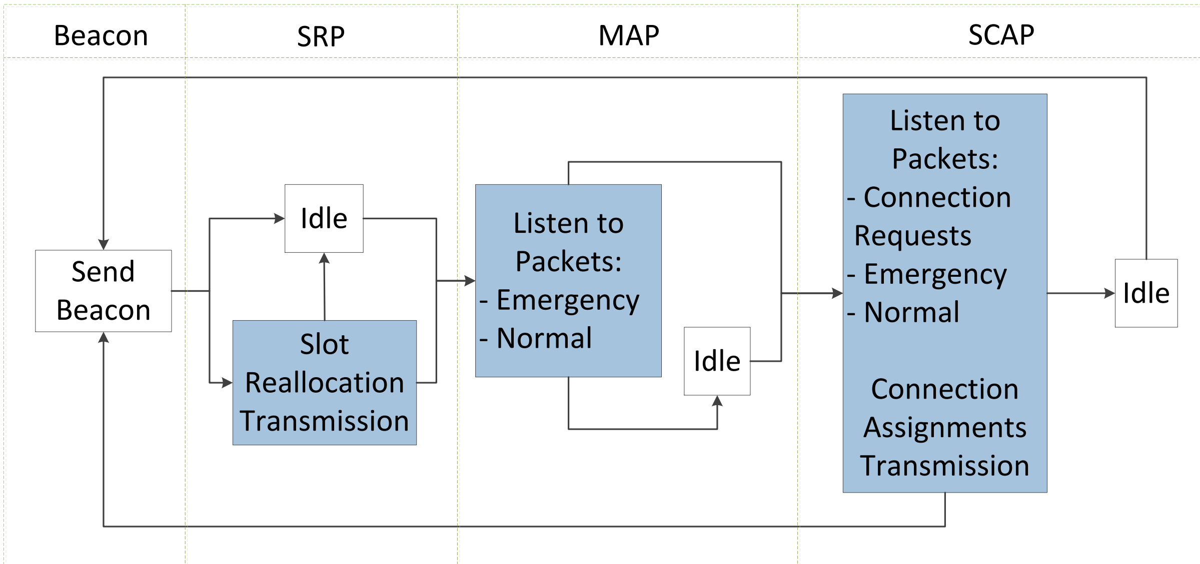

Figure 3.14. Hub states in SportsBAN

3.3.4 Final Slot Reallocation Algorithm

The Table 3.5 lists all the alert codes for the Slot Reallocation Algorithm. Two extra bits are used into each packet in the application layer for indicating the alert type. Normal packets send both bits with value of 0 (zero) indicating that there is no alert for the current packet. First bit with value of 0 (zero) and second bit with value of 1 (one) means a Low Battery Level alert, indicating the need of being the first node to transmit in the next beacon period before going to shut-down mode when the node battery is dead. First bit with value of 1 (one) and second bit with value of 0 (zero) means a High Buffer Level alert, indicating in advance that the sensor node is going to gather a lot of emergency data and it is going to need more slots in MAP for the next beacon period, avoiding emergency buffer overflow. Both bits (first and second) with value of 1 (one) means a medical alert, indicating it is a packet of the maximum priority that needs to be sent immediately in either MAP or SCAP phases.

Table 3.5. Alert Codes for the Slot Reallocation Algorithm in SportsBAN

First Bit	Second Bit	Alert Type
0	0	None
0	1	Low Battery Level
1	0	High Buffer Level
1	1	Emergency Data

The implementation uses Immediate Acknowledge (I-Ack) policy for all data packets rather than using Later Block Acknowledge (L-Ack) or Block Acknowledge (B-Ack) policies. Uplink requests are simplified to only ask for the number of slots needed (always 2 [two] for the proposed MAC protocol). Emergency packets have their own buffer, and are handled with higher priority than normal packets. The management packets that need to be acknowledged, have their own buffer, and are handled with higher priority than emergency packets. The Slot Reallocation Algorithm is described in ALGORITHM 3.1.

ALGORITHM 3.1. Slot Reallocation Algorithm in SportsBAN

```
If reallocation then
  Set RIB ← 1
  Set currentFirstFreeSlot ← SRP_length
  While Reallocation_Buffer_Alert is not empty do
    Set currentNode ← Reallocation_Buffer_Alert.pop()
    Set slotFactor ← CalculateSlotMultiplicatorFactor()
    Set assignedSlots ← scheduledAccesLength X slotFactor for
    currentNode
    Set startSlot ← currentFirstFreeSlot for currentNode
    Set endSlot ← currentFirstFreeSlot + assignedSlots for
    currentNode
    Set currentFirstFreeSlot ← currentFirstFreeSlot
                                + (endSlot - startSlot)
  End While
  Assign Default Slot Allocation to the remaining nodes
  Send Slot Reallocations in the next SRP
End If
```

The whole flow chart for the proposed MAC protocol, from the reception of the current beacon through the three phases SRP, MAP and SCAP until waiting for the next beacon, is depicted in the Figure 3.15.

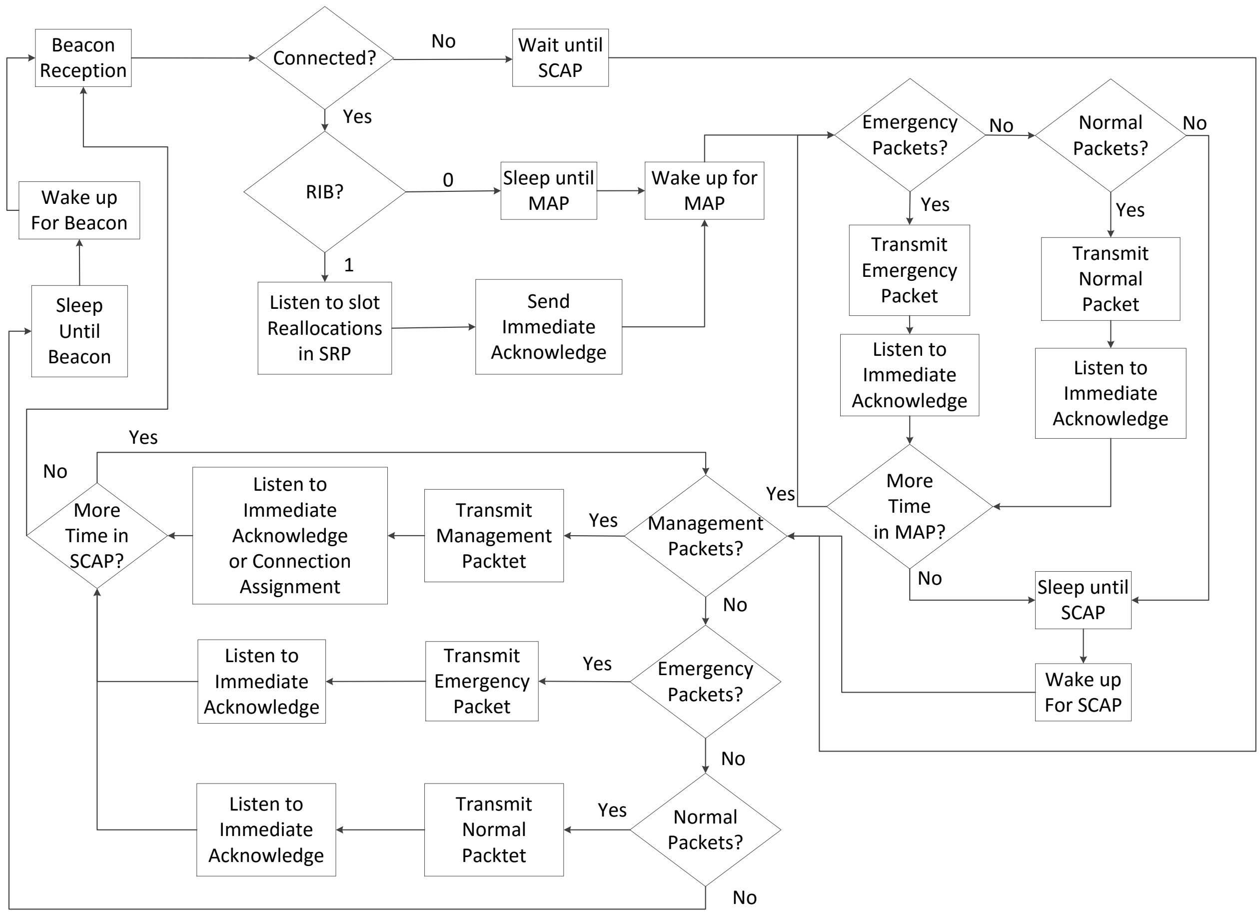

Figure 3.15. Flow chart of SportsBAN

3.3.5 Analysis

This section shows the comparative analysis between the proposed MAC protocol (SportsBAN) and the IEEE 802.15.6 MAC protocol. Since the original purpose of the MAC layer is to achieve maximum throughput, minimum delay, and to maximize the WBAN lifetime, the analysis addresses to the normal and emergency packet loss, the latency, and the average energy consumption in the WBAN.

3.3.5.1 Packet Loss

The contention during EAP and RAP phases for the IEEE 802.15.6 MAC protocol can cause packet loss when the channel is busy, while this can only be caused in the SportsBAN MAC protocol during SCAP phase. The fading channel in all phases for both MAC protocols can cause packet loss due to missing acknowledgement. When the normal traffic is high, it can cause packet loss due to normal buffer overflow for both MAC protocols. The high emergency traffic can cause packet loss due to emergency buffer overflow for the IEEE 802.15.6 MAC protocol. However, the proposed MAC protocol changes dynamically the number of assigned slots during MAP, giving more slots to those nodes with high emergency traffic and reducing the emergency buffer overflow probability.

The packet loss due to emergency buffer overflow can be compared to the water tank problem, where the tank is filled by a first tap A and it is drained by a second tap B. Knowing the time the tap A takes to fill the tank and the time the tap B takes to drain the tank, the filling rate of the tank can be calculated when both taps A and B are open, as long as the size of the tank is known.

The expressions (3.2) and (3.3) depict the filling rate of the emergency buffer for the IEEE 802.15.6 MAC protocol (BaselineBAN in the simulations) and the proposed MAC protocol (SportsBAN), respectively. Where, P is the filling rate of the emergency buffer in both protocols, Q is the emptying rate of the emergency buffer in BaselineBAN and R is the emptying rate of the emergency buffer in SportsBAN.

$$S_{baselineban} = P - Q \tag{3.2}$$

$$S_{sportsban} = P - R \tag{3.3}$$

It needs to be demonstrated that the expression (3.2) is higher than the expression (3.3). Given that P is the same for both protocols, it is only necessary to demonstrate that $Q > R$. The expressions (3.4) and (3.5) represent the emptying rates of the emergency buffer for BaselineBAN and SportsBAN, respectively.

$$Q = k \times q \times slots_{baselineban} \tag{3.4}$$

$$R = k \times q \times slots_{sportsban} \tag{3.5}$$

Where k is the ratio between the slots and the unit of time (ms for the simulations), q is the packet sending rate in packets per unit of time (packets/ms for the simulations). Given that k and q are the same for both protocols, It is only necessary to demonstrate that $slots_{baselineban} > slots_{sportsban}$. The number of dedicated slots for emergency traffic in BaselineBAN is the EAP length (3 for the simulations), while the number of dedicated slots for emergency traffic in SportsBAN is shown in the expression (3.6).

$$slots_{sportsban} = m \times scheduledAccessLength \tag{3.6}$$

Where m is a factor greater than one (4 for the simulations) and $scheduledAccessLength$ is two. Then, it could be deduced that the IEEE 802.15.6 MAC protocol displays more emergency buffer overflow than the proposed MAC protocol.

3.3.5.2 Latency

The normal and emergency packet latency in the WBAN can be caused by contention, high packet traffic (normal packets and especially emergency packets) and fading channel in both IEEE 802.15.6 MAC protocol and SportsBAN MAC protocol. The Figure 3.16 depicts the behavior of both protocols for normal and emergency traffic in the best case (blue color), the average case (green color) and the worst case (red color).

The best case for normal traffic in BaselineBAN, indicates the possibility of sending the normal packet during RAP with contention, while in SportsBAN, it indicates the possibility of sending the normal packet during MAP with no contention. The average case for normal traffic in BaselineBAN, indicates the possibility of sending the normal packet during RAP with contention or during MAP with no contention, while in SportsBAN, it indicates the possibility of sending the normal packet during MAP with no contention or during SCAP with contention. The worst case for normal traffic in BaselineBAN, indicates the need for waiting one whole beacon period in order to try to send the normal packet during RAP with contention, while in SportsBAN, it indicates the need for waiting one whole beacon period in order to try to send the normal packet during MAP with no contention.

The best case for emergency traffic in BaselineBAN, indicates the possibility of sending the emergency packet during EAP with contention, while in SportsBAN, it indicates the possibility of sending the emergency packet during MAP with no contention. There is no average case for emergency traffic in BaselineBAN, while the average case for emergency traffic in SportsBAN, indicates the possibility of sending the emergency packet during MAP with no contention or during SCAP with contention. The worst case for emergency traffic in BaselineBAN, indicates the need for waiting one whole beacon period in order to try to send the emergency packet during

EAP with contention, while in SportsBAN, it indicates the need for waiting one whole beacon period in order to try to send the emergency packet during MAP with no contention.

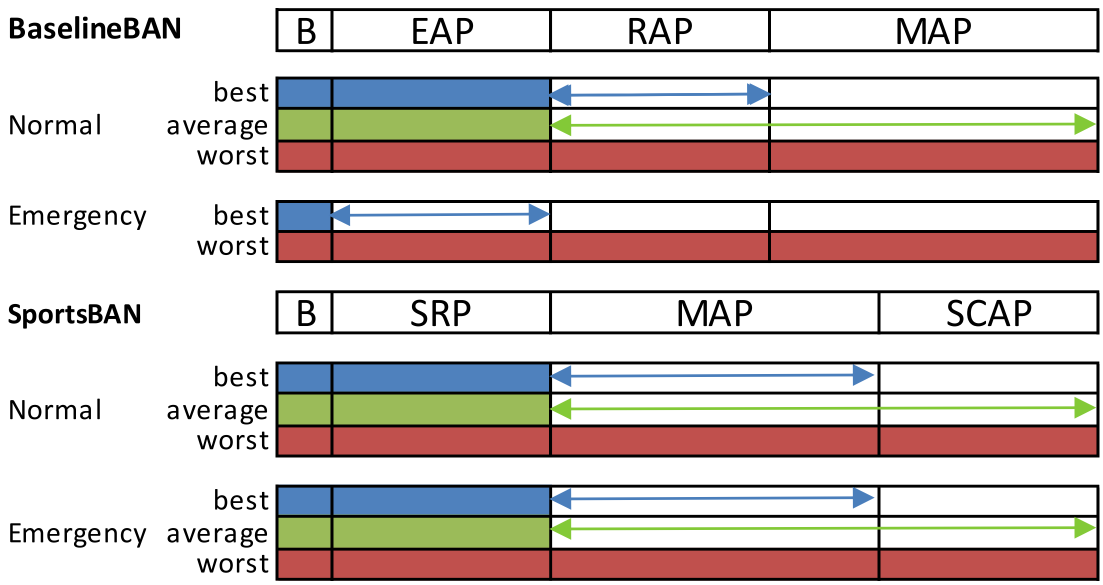

Figure 3.16. Latency behavior of SportsBAN

3.3.5.3 Energy Consumption

Since three of the main sources of energy waste in a WBAN are the packet collisions, the idle listening and the overhearing, and these three factors are presented with higher probability in contention phases, the quantity of slots during contention phases (EAP and RAP) of the IEEE 802.15.6 MAC protocol indicates more energy waste than the proposed MAC protocol (only during SCAP). High normal traffic is very common in Sports WBAN, so, there are only three cases to study depending on emergency traffic: (i) No emergency traffic; (ii) Low emergency traffic; and (iii) High emergency traffic.

The expression (3.7) shows the average power consumption per node in BaselineBAN.

$$P_{baselineban} = P_{beacon\_listen} + P_{EAP} + P_{RAP} + P_{MAP} \tag{3.7}$$

Where P_{beacon_listen} is the consumed energy for listening to the current beacon. P_{EAP}, P_{RAP} and P_{MAP} are the consumed energy during the EAP, RAP and MAP phases in Baseline, respectively.

The expressions (3.8), (3.9) and (3.10) represent the average power per node in BaselineBAN for the three aforementioned cases, respectively.

$$P_{baselineban\ 1} = P_{beacon\_listen} + \quad 0 \quad + P_{RAP} + P_{MAP} \tag{3.8}$$

$$P_{baselineban\ 2} = P_{beacon\_listen} + P_{EAP} + P_{RAP} + P_{MAP} \tag{3.9}$$

$$P_{baselineban\ 3} = P_{beacon\_listen} + P_{EAP} + P_{RAP} + P_{MAP} \tag{3.10}$$

The expression (3.11) depicts the average power consumption per node in SportsBAN.

$$P_{sportsban} = P_{beacon\_listen} + P_{SRP} + P_{MAP} + P_{SCAP} \tag{3.11}$$

Where P_{beacon_listen} is the consumed energy for listening to the current beacon. P_{SRP}, P_{MAP} and P_{SCAP} are the consumed energy during the SRP, MAP and SCAP phases in SportsBAN, respectively. The expressions (3.12), (3.13) and (3.14) represent the average power per node in the SportsBAN MAC protocol for the three aforementioned cases, respectively.

$$P_{sportsban\ case\ 1} = P_{beacon\_listen} + \quad 0 \quad + P_{MAP} + P_{SCAP} \tag{3.12}$$

$$P_{sportsban\ case\ 2} = P_{beacon\_listen} + \quad 0 \quad + P_{MAP} + P_{SCAP} \tag{3.13}$$

$$P_{sportsban\ case\ 3} = P_{beacon\_listen} + [P_{SRP}] + P_{MAP} + P_{SCAP} \tag{3.14}$$

Assuming that P_{MAP} for both protocols is almost the same, and that $P_{RAP} \sim P_{SCAP}$ because of the contention-based transmission, the difference in energy consumption is given by P_{EAP} in BaselineBAN and P_{SRP} in SportsBAN. Given that P_{SRP} is different from zero only twice per emergency event (i.e. the first time for changing the slot allocation and the second time for restoring the original slot allocation), it could be deduced that the average consumed energy by the IEEE 802.15.6 MAC protocol is higher than the average consumed energy by the proposed MAC protocol.

3.3.6 Final Experimental Results

3.3.6.1 Final Simulation Parameters

The simulated network was composed most of the time by ten nodes: nine sensor nodes and one hub. The center sensor is the hub and it is assumed that it never goes to sleep mode and it is always ON. The Figure 3.17 shows the star topology for the simulation scenario.

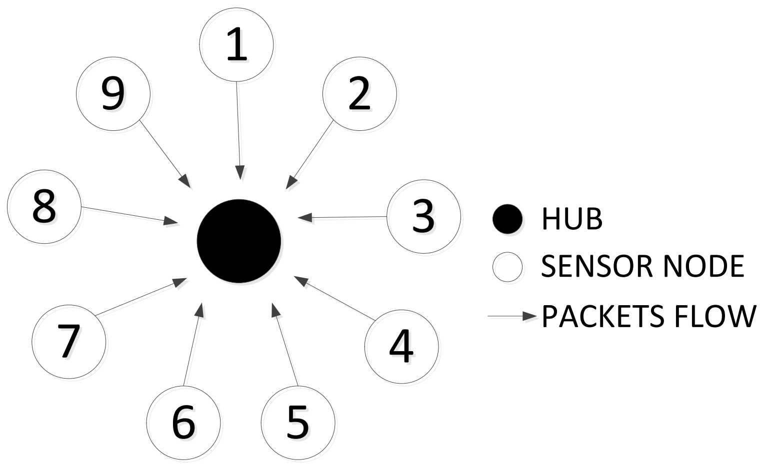

Figure 3.17. Star topology for the simulation scenario of SportsBAN

Each time an emergency event happened, the packet rate was increased by ten times during 5s. The Bypass Routing Protocol was used in the network layer. This protocol does not implement any routing because of the star topology used. The additional simulation parameters for the application, MAC and physical layers are listed in the Table 3.6. The beacon period length was 32 slots for both the IEEE 802.15.6 Standard and SportsBAN MAC protocol. The MAP length was 26 slots for both the IEEE 802.15.6 Standard and SportsBAN MAC protocol. The remaining six slots were distributed between EAP (three slots) and RAP (three slots) phases for the IEEE 802.15.6 Standard, and between SRP (three slots) and SCAP (three slots) phases for SportsBAN MAC protocol. The values for the parameters: allocation slot length, beacon period length, scheduled access length, scheduled access period, and contention slot length were the same in both protocols in order to keep fairness in the comparison.

Table 3.6. Simulation Parameters for SportsBAN

Layer	Parameter	Value
Application	Packet Rate (per second)	20
	Default Priority for nodes	2

Layer	Parameter	Value
	Constant Data Payload (in bytes)	80
MAC	Maximum Transmission Tries	2
	Normal Buffer size (packets)	32
	Emergency Buffer size (packets)	32
	Packet Overhead (bytes)	7
	Allocation Slot Length (ms)	10
	Beacon Period Length (slots)	32
	SRP Length (slots)	3
	MAP Length (slots)	26
	SCAP Length (slots)	3
	Scheduled Access Length (slots)	2
	Scheduled Access Period	1
	Contention Slot Length (ms)	0.36
PHY	Topology	Star
	TX Output Power (dBm)	-10
	Baseline Node Power (mW)	10
	PHY Layer Overhead (bytes)	6
	Data Rate (kbps)	1024

3.3.6.2 Final Results

Five different simulations were made for the comparisons with the other three MAC protocols. In the first simulation the number of nodes was modified from 2 to 10. In the second simulation the packet rate was modified from 5pkt/s to 25pkt/s. In the third simulation the total simulation time was varied from 400s to 2000s. In the fourth simulation the number of emergency events was increased from 1 to 5. In the last simulation none of the parameters were changed in order to study the latency for emergency and normal traffic. The Energy Waste Index was introduced in order to study the energy effectiveness. It was calculated as the ratio between the percentage of the packet loss and the average consumed energy. The lower the index the better the energy effectiveness of the protocol.

For the first simulation, the number of nodes was changed incrementally from two to ten (more than 10 nodes in a sportsman is comfortless). The simulation time was 300s, and the packet rate was 20pkt/s. There was one emergency event at t=150s with the duration of 5s. The percentage of the packet loss for emergency and normal traffic, when the total number of nodes was changed in the WBAN, are depicted in Figure 3.18 and Figure 3.19 respectively. The proposed MAC protocol showed the lowest percentage of emergency (almost 0% no matter the number of nodes) and normal (lower than 4%) packet loss because of the slot reallocation algorithm, which assigns more dedicated slots during MAP phase for the nodes with high emergency traffic, and then restores the original slot allocation when the emergency event is over. The IEEE 802.15.4 MAC protocol showed the worst percentage of emergency packet loss, followed by T-MAC and the IEEE 802.15.6 MAC protocol. The behavior of the IEEE 802.15.4 MAC protocol and T-MAC with the percentage of emergency packet loss when we increase the number of nodes in the WBAN, demonstrates why we should not use WSN MAC protocols directly on WBANs. The IEEE 802.15.4 MAC protocol also showed the worst percentage of normal packet loss, followed by the IEEE 802.15.6 MAC protocol and T-MAC protocol. Until six nodes, the IEEE 802.15.4 showed a good behavior with the percentage of normal packet loss, but for eight and ten nodes this percentage was more than 28%.

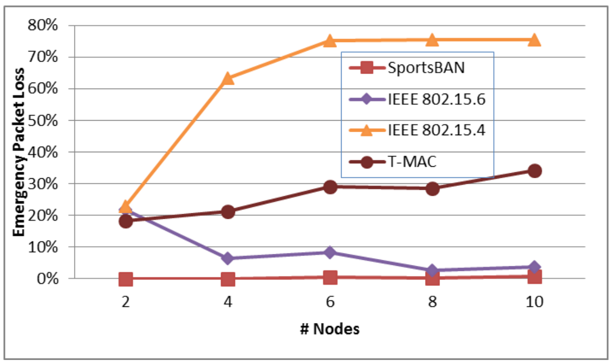

Figure 3.18. Emergency Packet Loss vs Number of nodes

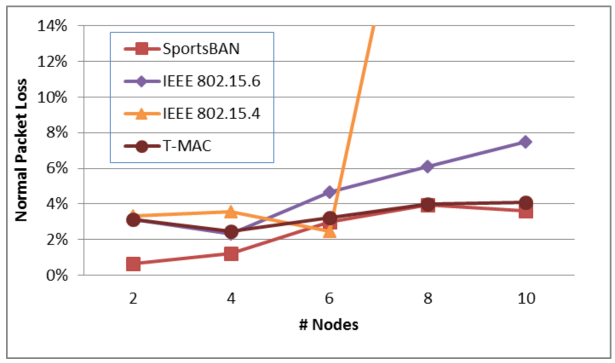

Figure 3.19. Normal Packet Loss vs Number of nodes

The Energy Waste Index for emergency and normal traffic, when the number of nodes was changed in the WBAN, is depicted in Figure 3.20 and Figure 3.21 respectively. The Energy Waste Index for the proposed MAC protocol was almost zero (the best energy effectiveness) for emergency traffic. SportsBAN also showed the best energy effectiveness for normal traffic, even with the good performance of T-MAC protocol with normal traffic nodes. The IEEE 802.15.4 MAC protocol showed the worst Energy Waste Index for emergency and normal traffic due to the poor performance of the packet loss in both emergency (more than 70% after 6 nodes) and normal (more than 28% after 6 nodes) traffic. The energy effectiveness of the IEEE 802.15.6 MAC protocol for both emergency and normal traffic was better than T-MAC and the IEEE 802.15.4 MAC protocol. The Energy Waste Index is directly proportional to the percentage of the packet loss and this is the reason why the Figure 3.18 and the Figure 3.20 are approaching. The same case for the Figure 3.19 and the Figure 3.21. The behavior of the IEEE 802.15.4 MAC protocol and T-MAC protocol with the emergency traffic when we increase the number of nodes in the WBAN, demonstrates why we should not use WSN MAC protocols directly on WBANs.

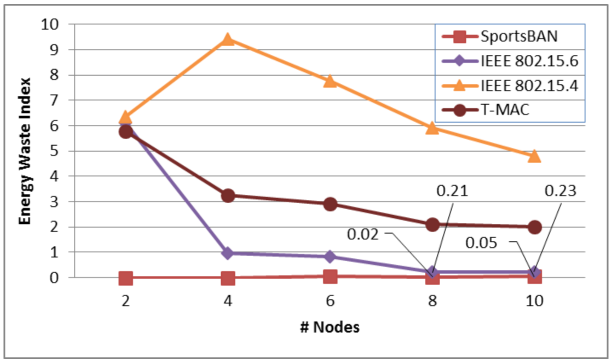

Figure 3.20. Energy Waste Index for emergency traffic vs Number of nodes

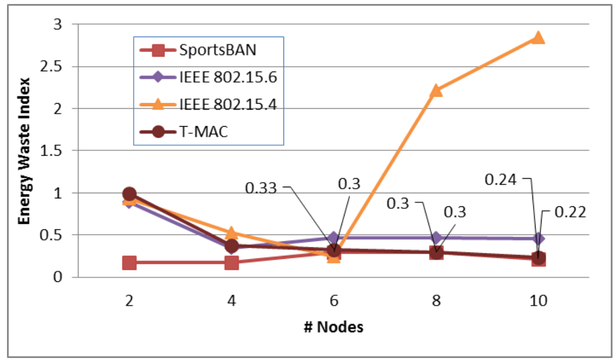

Figure 3.21. Energy Waste Index for normal traffic vs Number of nodes

In the second simulation, the packet rate was changed incrementally from 5pkt/s to 25pkt/s. The simulation time was 300s, and the number of nodes was 10. There were four emergency events at t=60s, t=120s, t=180s and t=240s with the duration of 5s each one. The percentage of emergency packet loss and the Energy Waste Index, when the packet rate was changed in the WBAN, are depicted in Figure 3.22 and Figure 3.23 respectively. The proposed MAC protocol showed the lowest percentage of emergency packet loss because of the slot reallocation algorithm. For the simulations, the emergency packet rate was ten times the normal packet rate. It means that a node with an emergency event, sent 250 packets per second while the remaining normal nodes sent 25 packets per second. The proposed MAC protocol showed the best Energy Waste Index for emergency traffic (almost 0). The IEEE 802.15.4 MAC protocol showed the worst energy effectiveness because of its poor performance with the emergency packet loss (more than 50% after 5pkt/s). The IEEE 802.15.6 MAC protocol had a performance as good as SportsBAN until 20pkt/s. After that, SportsBAN was better. The simulation showed how SportsBAN MAC protocol offers a very good emergency packet loss despite the packet rate in the WBAN. With the increase of the packet rate, the WBAN traffic increases and the probability of the packet loss due to buffer overflow does also. The behavior of the IEEE 802.15.4 MAC protocol and T-MAC protocol with the emergency traffic when we increase the packet rate, demonstrates why we should not use WSN MAC protocols directly on WBANs.

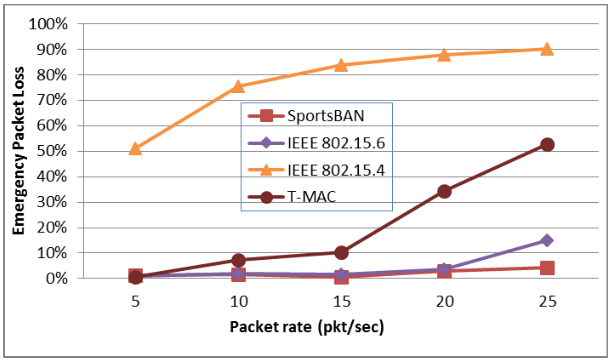

Figure 3.22. Emergency Packet Loss vs Packet rate

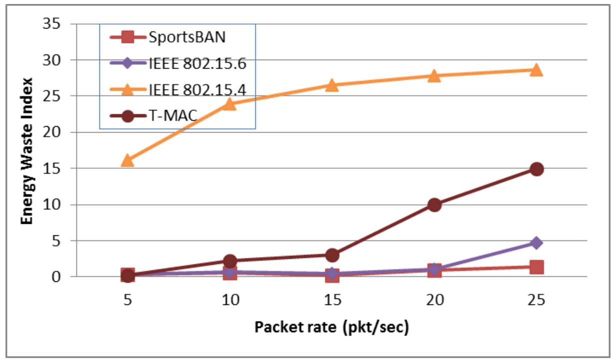

Figure 3.23. Energy Waste Index for emergency traffic vs Packet rate

For the third simulation, the simulation time was changed incrementally from 400s to 2000s (~33 min of workout). The packet rate was 20pkt/s, and the number of nodes was 10. There were three emergency events with the duration of 5s each one. The percentage of emergency packet loss and Energy waste Index, when the simulation time was changed in the WBAN, are depicted in Figure 3.24 and Figure 3.25 respectively. The proposed MAC protocol showed the lowest percentage of emergency packet loss (almost 0% no matter the simulation time) because of the slot reallocation algorithm. The proposed MAC protocol showed the best Energy Waste Index for emergency traffic (almost 0). The IEEE 802.15.4 MAC protocol showed the worst Energy Waste Index because of its poor performance with the emergency packet loss (more than 80%). The Figure 3.25 shows how the IEEE 802.15.4 and T-MAC protocols improve the Energy Waste Index with the increase of the simulation time, but this is due to the increase of the average energy consumption, which is the denominator in the ratio calculation of the Energy Waste Index. The behavior of the IEEE 802.15.4 MAC protocol and T-MAC protocol with the emergency traffic when we increase the simulation time, demonstrates why we should not use WSN MAC protocols directly on WBANs.

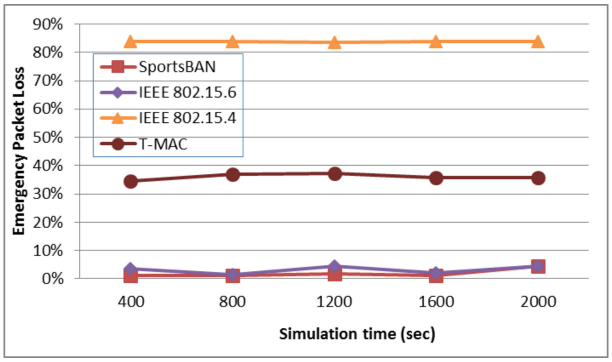

Figure 3.24. Emergency Packet Loss vs Simulation time

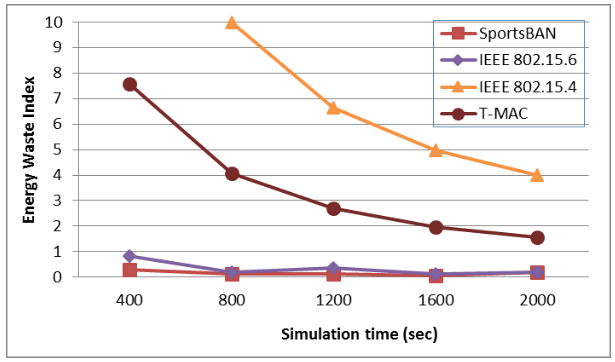

Figure 3.25. Energy Waste Index for emergency traffic vs Simulation time

In the fourth simulation, the number of emergency events was changed incrementally from 1 to 5. Each emergency event had the duration of 5s. The simulation time was 300s, the packet rate was 20pkt/s, and the number of nodes was 10. The percentage of emergency packet loss and the Energy Waste Index, when the number of emergency events was changed in the WBAN, are depicted in Figure 3.26 and Figure 3.27 respectively. The proposed MAC protocol showed the lowest percentage of emergency packet loss (almost 0% no matter the total number of emergency events) because of the slot reallocation algorithm. The proposed MAC protocol showed the best Energy Waste Index for emergency traffic (almost 0). The IEEE 802.15.4 MAC protocol showed the worst energy effectiveness because of its poor performance with the emergency packet loss (more than 70%). The IEEE 802.15.6 MAC protocol showed a performance as good as SportsBAN, but the percentage of emergency packet loss and the energy effectiveness were a little higher. The behavior of the IEEE 802.15.4 MAC protocol and T-MAC protocol with the emergency traffic when we increase the number of emergency events in the WBAN, demonstrates why we should not use WSN MAC protocols directly on WBANs. As the emergency events were not at the same time, the behavior of all protocols stayed almost the same when we change the number of emergency events in the WBAN.

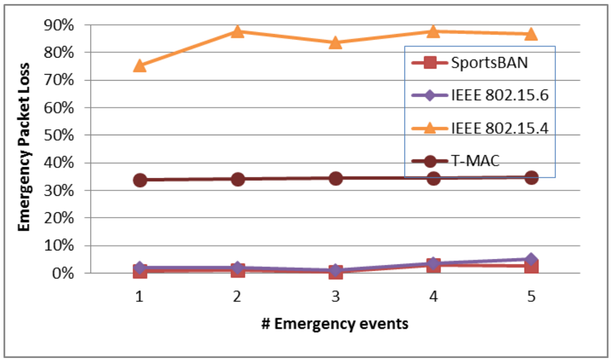

Figure 3.26. Emergency Packet Loss vs Number of emergency events

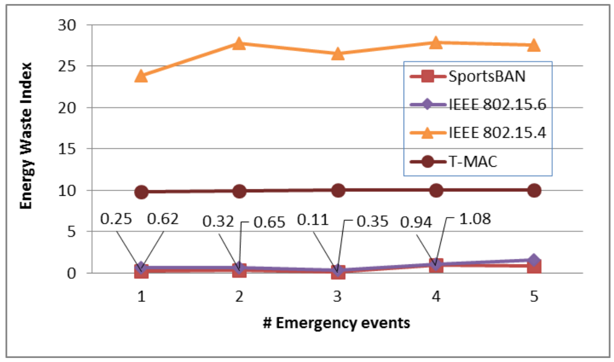

Figure 3.27. Energy Waste Index for emergency traffic vs Number of emergency events

For the final simulation, the simulation time was 300s, the number of nodes was 6, the packet rate was 20pkt/s and there was one emergency event at t=150s with the duration of 5s. The latency distribution for emergency packets and normal packets are depicted in Figure 3.28 and Figure 3.29 respectively. The number of emergency packets with the lowest latency ([0, 100) ms) in the proposed MAC protocol was much higher than the other three MAC protocols because of the slot reallocation algorithm, the lack of contention for emergency traffic during the MAP phase, and besides, the additional contention phase (SCAP) for emergency and normal traffic into each beacon period. The number of normal packets with low latency ([0, 160) ms) in the proposed MAC protocol was higher than the other MAC protocols, excepting the IEEE 802.15.4 MAC protocol, because of the poor average performance of the latter with emergency traffic. With the IEEE 802.15.4 MAC protocol, almost 90% of the emergency traffic was delivered with the latency of more than 400 ms, while almost 90% of the normal traffic was delivered with the latency of fewer than 120 ms. This good behavior of the latency with normal traffic was the trade-off to the 28% of normal packet loss in the Figure 3.19. The Figure 3.28 and the Figure 3.29 supports the analysis of the latency depicted in the Figure 3.16.

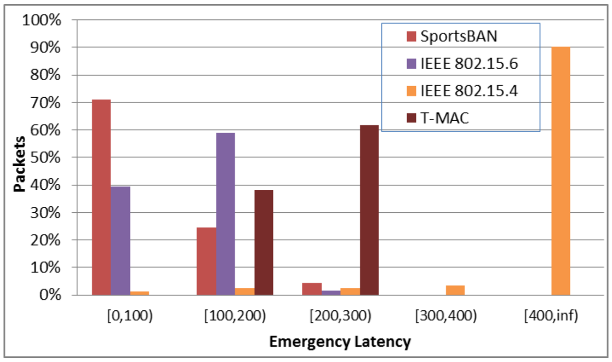

Figure 3.28. Emergency Latency in SportsBAN

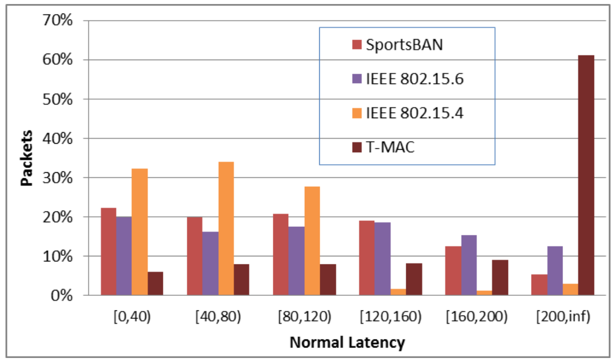

Figure 3.29. Normal Latency in SportsBAN

3.3.7 Conclusions

In this chapter, a new MAC protocol for WBANs was proposed in the section 3.2, based on the IEEE 802.15.6 Standard MAC protocol, but taking into account special characteristics that can be presented in some WBANs such as quantity of packets in normal traffic and emergency traffic. The proposed MAC protocol proposes two new phases into each beacon period such as Slot Reallocation Phase (SRP) for slot reallocations, and Management and Emergency Phase (MEP) for management packets and additional emergency traffic.

For evaluating the performance of the proposed MAC protocol, we used two variables: the energy consumption and the emergency packet latency and we showed that the proposed MAC protocol outperformed the IEEE 802.15.6 MAC protocol when we increased the emergency probability in each sensor node or the total number of nodes in the WBAN. The average improvement of the energy efficiency in the whole WBAN was almost 2% more when we use the proposed MAC protocol.

In the section 3.3, SportsBAN, a new MAC protocol for WBANs was proposed, based on the MAC protocol proposed in the section 3.2, but taking into account special features that exist in Sports WBANs such as quantity and frequency of packets in normal and emergency traffic. SportsBAN uses the same Slot Reallocation Phase (SRP) for slot reallocations and proposes a Special Contention Access Phase (SCAP) for management traffic like connection requests, and additional emergency and normal traffic.

The proposed MAC protocol outperformed the IEEE 802.15.6 MAC protocol, the IEEE 802.15.4 MAC protocol and the T-MAC protocol in the percentage of emergency and normal packet loss and latency, while maintaining a similar energy consumption as the IEEE 802.15.6 MAC protocol. However, when the new comparison parameter, the Energy Waste Index, was calculated, it showed that SportsBAN protocol had a better energy effectiveness than the other protocols for emergency and normal traffic. The IEEE 802.15.4 MAC protocol always showed the lowest energy consumption per node, but the worst Energy Waste Index because of its poor performance with the packet loss (emergency and normal traffic) and the latency (emergency and normal traffic). The T-MAC protocol performance demonstrated why MAC protocols for WSNs cannot be used directly over WBANs.

CHAPTER 4 RELIABLE TRANSPORT PROTOCOL BASED ON LOSS RECOVERY AND FAIRNESS FOR SPORTS WIRELESS BODY AREA NETWORKS

This chapter presents a new transport protocol based on loss recovery and fairness to assure reliability for WBANs used in sports applications. The protocol is based on the MAC protocol proposed in Chapter 3. It detects out-of-sequence packets and requests retransmission of the lost packets during the SRP phase. This chapter is divided in three main sections. The section 4.1 presents the proposed transport protocol with its packet loss detection algorithms. The section 4.2 presents a comparative analysis of the packet loss between the proposed transport protocol and the IEEE 802.15.6 standard. The section 4.3 shows the simulation results comparing the IEEE 802.15.6 standard with the SportsBAN MAC protocol along with the proposed transport protocol presented in Chapter 3.

4.1 Proposed Transport Protocol

The main causes of the packet loss in WBANs are contention, fading channel and buffer overflow. A WBAN can have heterogeneous traffic and different transmissions rates and frequencies from its sensor nodes. It could be assumed there is no congestion in the hub due to its buffer size. A lost packet could be a normal, an emergency, or a management packet (connection assignment or connection request). For the management packets, there is no need of a recovery scheme because the MAC protocol guarantees the connection of each node to the WBAN.

The proposed transport protocol uses cross-layer design in order to provide reliability through loss recovery and fairness. Both loss recovery and fairness schemes are implemented over the MAC layer, using SportsBAN. The transport protocol adds Loss Recovery and Fairness (LR&F) to the SportsBAN protocol.

4.1.1 Node and Hub States

All the lost (normal and emergency) packet retransmissions are made during the SRP phase for energy efficiency. The TDMA protocol is used during the SRP phase, then, there is no contention for the retransmissions requested by the hub and sent by the nodes. The Figure 4.1 depicts the node states for the SportsBAN MAC protocol working along with the proposed transport protocol. After receiving a beacon, the node reads the Retransmission Indicator Bit (RIB) and it has to decide if it goes to sleep mode or it listens to retransmission requests from the hub during the SRP phase. The node sends all the lost packet retransmissions during the SRP phase. Then, it will be able to send emergency and normal traffic during the MAP phase and additional emergency and normal traffic during the SCAP phase.

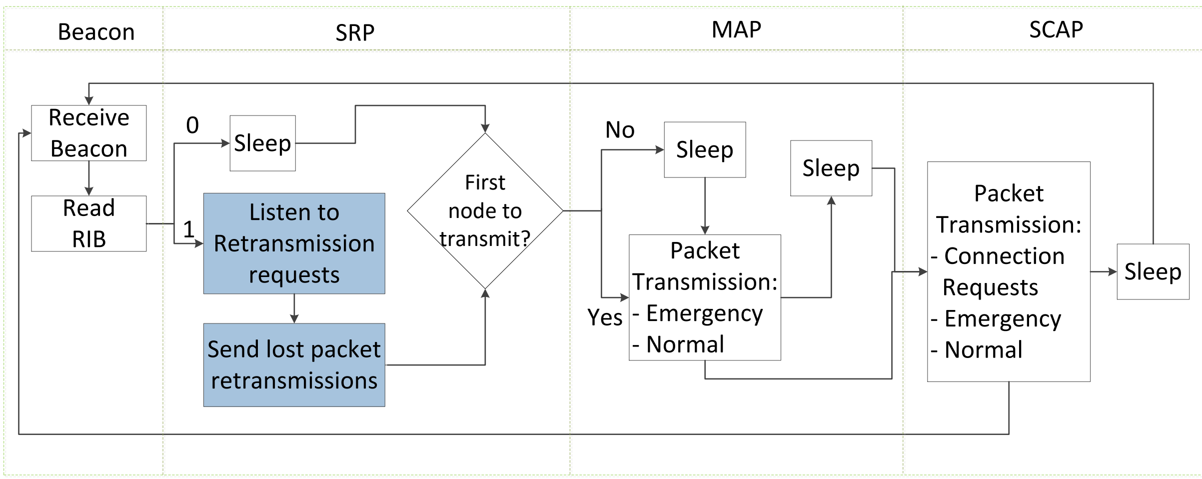

Figure 4.1. Node states in SportsBAN + LR&F

The Figure 4.2 depicts the hub states for the SportsBAN MAC protocol working along with the proposed transport protocol. After sending a beacon, the hub can go to idle mode or it can send lost packet retransmission requests to all sensor nodes. The hub uses the TDMA protocol for using all slots during the SRP phase, avoiding contention with the sensor nodes. After receiving the lost packet retransmissions from the nodes, the hub can go to idle mode during the SRP phase or start to listen to emergency and normal traffic during the MAP phase. Finally, the hub will be listening to additional emergency and normal traffic from connected nodes, listening to connection requests from unconnected nodes, and sending connection assignments.

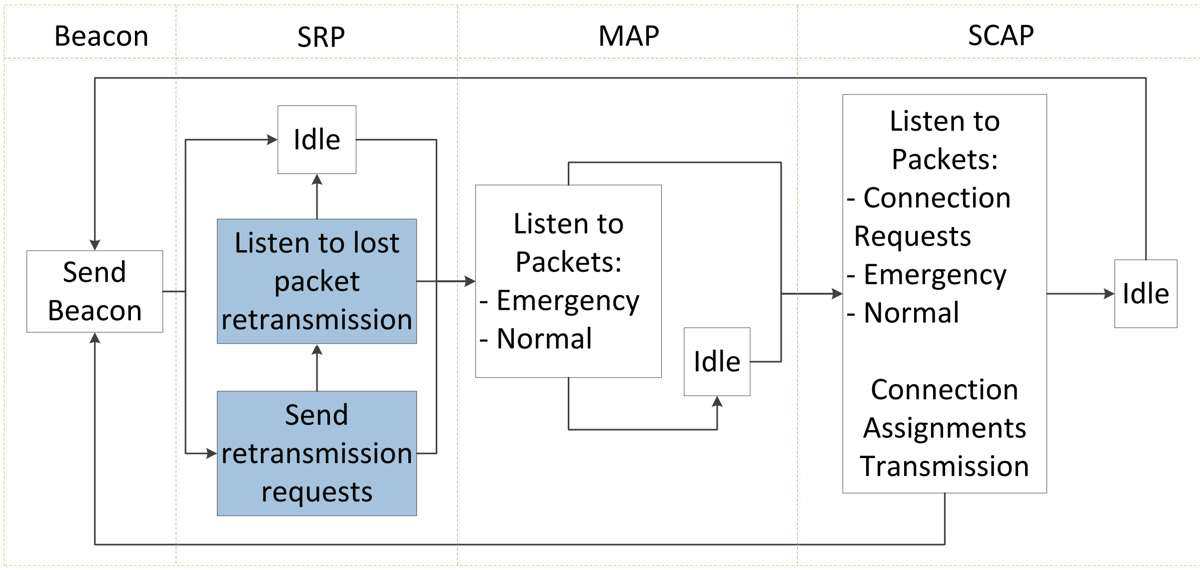

Figure 4.2. Hub states in SportsBAN + LR&F

Each node detects the lost packets using the lack of acknowledgment of the normal and emergency traffic and the dropping of packets due to a busy channel or buffer overflow in the MAC layer. Each node avoids the retransmission of duplicate packets, retransmitting only when a lost packet retransmission request arrives from the hub.

The hub detects the out-of-sequence packets in the MAC layer with no need of going up until the application layer. When the hub detects out-of-sequence packets during MAP and SCAP phases, it creates the lost packet retransmission requests and using a Fairness Index, it sends the corresponding requests during the SRP phase. Each node verifies the RIBs (Reallocation Indicator Bit and Retransmission Indicator Bit) in each beacon in order to know if it will be in listening mode (slot reallocations or retransmission requests) or in sleeping mode during the SRP phase.

The hub calculates the Fairness Index for each node using the ratio between the number of lost packets and the total number of received packets, in order to guarantee fairness for the whole network. Each node buffers only the more recent lost packets because the size of the lost packet buffer is always small (four for the simulations).

4.1.2 Packet Loss Detection

The packet loss detection algorithms used by the hub and by each node in the WBAN are described in ALGORITHM 4.1 and ALGORITHM 4.2, respectively. The hub buffers all out-of-sequence packet numbers detected for each node. When the sequence number of the current packet is not the expected number, the hub buffers all lost packet numbers between the two sequence numbers. Then, it uses the RIB (Retransmission Indicator Bit) in order to warn all nodes about the lost packet retransmission requests it is going to make in the next SRP phase. Finally, the hub creates all lost packet retransmission requests.

ALGORITHM 4.1. Packet Loss Detection in the hub

```
Get sequenceNumber
If sequenceNumber > lastSequenceNumber + 1 then
  Set i ← lastSequenceNumber + 1
  Set node ← nodeID
  While i < sequenceNumber do
    RetransmBuffer[node].push(i)
    i ← i + 1
  End While
  Set RIB ← Retransmission
End If
Create All Lost Packet Retransmission Requests
```

The sensor nodes buffer the lost packets caused either by a busy channel or buffer overflow. The maximum number of lost packets buffered for each node is four (for the simulations). It means each node will always have the last four lost packets and it will not be able to retransmit oldest packets. The maximum number of retransmissions in the MAC layer, before the node considers a packet as lost is two (for the simulations). This is called a packet loss caused by a busy channel. The node can also consider a packet as lost when the packet does not fit in the current buffer. This is called a packet loss caused by buffer overflow.

ALGORITHM 4.2. Packet Loss Detection in the node

```
Set maxLostBufferSize ← 4
Set maxPacketTries ← 2
If numTransmissions + numFails = maxPacketTries then
  If LostBuffer.size = maxLostBufferSize then
    LostBuffer.pop()
  End If
  LostBuffer.push(currentPacket)
End If
If currentPacket does not fit in currentBuffer then
  If LostBuffer.size = maxLostBufferSize then
    LostBuffer.pop()
  End If
  LostBuffer.push(currentPacket)
End If
```

4.1.3 Lost Packet Retransmission Requests Creation

The lost packet retransmission requests creation algorithm is described in ALGORITHM 4.3. The hub calculates the Fairness Index for each node as the ratio between the number of lost packets from the node and the total number of received packets from the node. Then, the hub creates all the lost packet retransmission requests taking on account the calculated Fairness Index. Finally, the hub sends all the retransmission requests during the next SRP phase.

ALGORITHM 4.3. Lost Packet Retransmission Requests Creation

```
Calculate Fairness_Index for each node in RetransmBuffer
Sort RetransmBuffer using Fairness_Index
For each node m in RetransmBuffer do
  For each packet n in RetransmBuffer[m] do
    Create Lost Packet Retransmission Request of packet n from
    node m
  End For each
End For each
Send Lost Packet Retransmission Requests in next SRP
```

4.2 Analysis

A comparative analysis between the proposed transport protocol and the IEEE 802.15.6 Standard is presented in this section. A busy or fading channel and the buffer overflow are the most important causes of the packet loss. The expression (4.1) depicts the total number of Lost Packets in a WBAN.

$$LP_{TOTAL} = LP_{bc} + LP_{fc} + LP_{bo} \tag{4.1}$$

Where LP_{bc} is the number of lost packets due to a busy channel, LP_{fc} is the number of lost packets due to a fading channel, and LP_{bo} is the number of lost packets due to buffer overflow (normal or emergency packets).

The IEEE 802.15.6 Standard offers contention in EAP (Exclusive Access Phase) and RAP (Random Access Phase) during each beacon period and it can cause packet loss when the channel is busy. The expressions (4.2) and (4.3) depict the total number of lost packets of the IEEE 802.15.6 Standard with no emergency traffic (n) and with emergency traffic (e), respectively.

$$LP_{802.15.6(n)} = LP_{bc[RAP]} + LP_{fc} + LP_{nbo[EAP]} \tag{4.2}$$

$$LP_{802.15.6(e)} = LP_{bc[EAP]} + LP_{bc[RAP]} + LP_{fc} + LP_{nbo[EAP]} + LP_{ebo[RAP]} + LP_{ebo[MAP]} \tag{4.3}$$

Where LP_{nbo} is the number of lost packets due to normal buffer overflow and LP_{ebo} is the number of lost packets due to emergency buffer overflow. $[EAP]$, $[RAP]$ and $[MAP]$ indicate in which of the three phases of the IEEE 802.15.6 Standard the packets were lost.

The expressions (4.4) and (4.5) depict the total number of lost packets of the proposed transport protocol with no emergency traffic (n) and with emergency traffic (e), respectively.

$$LP_{proposed(n)} = LP_{bc[SCAP]} + LP_{fc} + LP_{nbo[SRP]} - RLP_{[SRP]} \tag{4.4}$$

$$\begin{aligned} LP_{proposed(e)} = {} & LP_{bc[SCAP]} + LP_{fc} + LP_{nbo[SRP]} + LP_{nbo[MAP]} + LP_{nbo[SCAP]} \\ & + LP_{ebo[SRP]} - RLP_{[SRP]} \end{aligned} \tag{4.5}$$

Where $RLP_{[SRP]}$ is the number of Retransmitted Lost Packet during the SRP phase. $[SCAP]$, $[SRP]$ and $[MAP]$ indicate in which of the three phases of the proposed transport protocol the packets were lost.

The RAP phase in the IEEE 802.15.6 Standard and the SCAP phase in the proposed transport protocol are contention phases and they use the CSMA/CA mechanism. The length of the EAP phase in the IEEE 802.15.6 Standard and the SRP phase in the proposed transport protocol are the same (three for the simulations). Only the proposed transport protocol offers Retransmission of Lost Packets (indicated with the negative factor RLP in expressions 4.4 and 4.5). It could be deducted from the expressions (4.2) and (4.4) that the total lost packets with no emergency traffic in the IEEE 802.15.6 Standard is higher than the proposed transport protocol. Moreover, in presence of emergency traffic, the proposed protocol shows emergency buffer overflow only during the SRP phase, while the IEEE 802.15.6 Standard shows it during RAP and MAP phases. Then, it could be deducted from the expressions (4.3) and (4.5) that the total lost packets with emergency traffic in the IEEE 802.15.6 Standard is higher than the proposed transport protocol.

4.3 Experimental Results

4.3.1 Simulation Parameters

The simulated network was composed of six nodes: five sensor nodes and one hub. The hub (in the center) was in the right hip. There were two sensor nodes over the wrists (2 and 5), two sensor nodes over the ankles (3 and 4) and one sensor node over the chest (1). The Figure 4.3 shows the star topology for the simulation scenario.

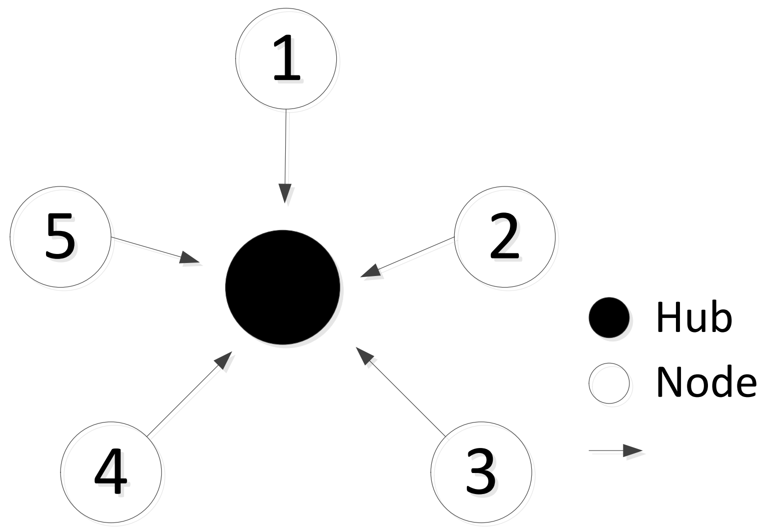

Figure 4.3. Star topology for the simulation scenario of SportsBAN + LR&F

The packet rate for all sensors was 20pkt/s. Each time an emergency event happened, the packet rate was increased by ten times during 5s. There was no need of a special routing protocol because of the network star topology. The additional simulation parameters for the transport, MAC and physical layers are listed in the Table 4.1. The beacon period length was 32 slots for both the IEEE 802.15.6 Standard and SportsBAN MAC protocol. The MAP length was 26 slots for both the IEEE 802.15.6 Standard and SportsBAN MAC protocol. The remaining six slots were distributed between EAP (three slots) and RAP (three slots) phases for the IEEE 802.15.6 Standard, and between SRP (three slots) and SCAP (three slots) phases for SportsBAN MAC protocol. The values for the parameters: scheduled access length and scheduled access period (one) were the same in both protocols in order to keep fairness in the comparison.

Table 4.1. Simulation Parameters for SportsBAN + LR&F

Layer	Parameter	Value
Transport	Lost Packet Buffer Size	4
	Maximum Lost Packet Retransmission Requests	1
MAC	Beacon Period Length (slots)	32
	SRP Length (slots)	3
	MAP Length (slots)	26
	SCAP Length (slots)	3
	Scheduled Access Length (slots)	2
PHY	TX Output Power (dBm)	-10
	Baseline Node Power (mW)	10

4.3.2 Simulation Results

The Energy Waste Index was introduced in order to study the energy effectiveness of the proposed transport protocol. It was calculated as the ratio between the percentage of the packet loss and the average consumed energy. The lower the index the better the energy effectiveness of the protocol. Two different simulations were made for the comparisons of the percentage of the packet loss and the Energy Waste Index: (i) with emergency events and (ii) without emergency events. For the first simulation the packet rate was modified from 5pkt/s to 25pkt/s with no emergency events. In the second simulation the packet rate was modified from 5pkt/s to 25pkt/s with one emergency event occurring at 150s during 5s in one specific sensor node. The total simulation time was always 300s.

The percentage of the packet loss when the packet rate is changed without emergency traffic in the WBAN is depicted in Figure 4.4. The SportsBAN MAC protocol along with the proposed transport protocol (LR&F) showed an average lower percentage of the packet loss than the SportsBAN MAC protocol alone and the IEEE 802.15.6 standard. This is due to the detection of out-of-sequence packets and the creation of lost packet retransmission requests for those packets. These retransmission requests are sent by the nodes during the SRP phase where there is no contention between nodes due to the TDMA protocol used by the hub. This simulation supports the behavior without emergency traffic of the IEEE 802.15.6 standard and the SportsBAN + LR&F described in the expressions (4.2) and (4.4) respectively. The proposed transport protocol (LR&F) adds a negative factor in the expression (4.4) and offers a fewer total number of lost packet when there is no emergency traffic in the WBAN. With the increase of the packet rate in the nodes, the percentage of the total packet loss decreases for the three compared solutions because the normal traffic in the WBAN increases and the total number of lost normal packets is not proportional.

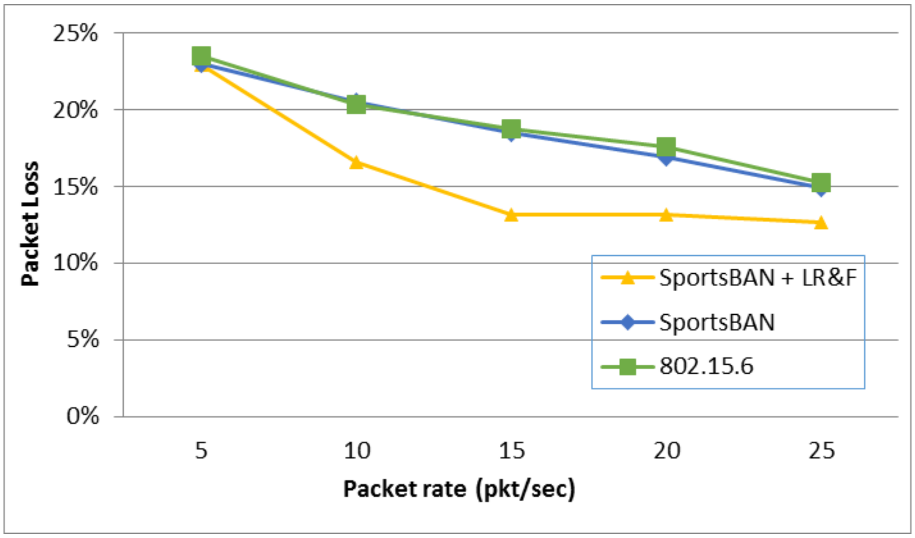

Figure 4.4. Packet loss without emergency traffic vs Packet rate

The percentage of the packet loss when the packet rate is changed with emergency traffic in the WBAN is depicted in the Figure 4.5. Again, the SportsBAN MAC protocol along with the proposed transport protocol (LR&F) showed an average lower percentage of the packet loss than the SportsBAN MAC protocol alone and the IEEE 802.15.6 standard. All the lost emergency packet retransmission are made during the SRP phase using non-contention transmission due to the TDMA protocol the hub uses. This simulation supports the behavior with emergency traffic of the IEEE 802.15.6 standard and the SportsBAN + LR&F described in the expressions (4.3) and (4.5) respectively. The proposed transport protocol (LR&F) adds a negative factor in the expression (4.5) and offers a fewer total number of lost packet when there is emergency traffic in the WBAN. With the increase of the packet rate in the nodes, the percentage of the total packet loss decreases for the three compared solutions because the normal and emergency traffic in the WBAN increases and the total number of lost normal and emergency packets is not proportional.

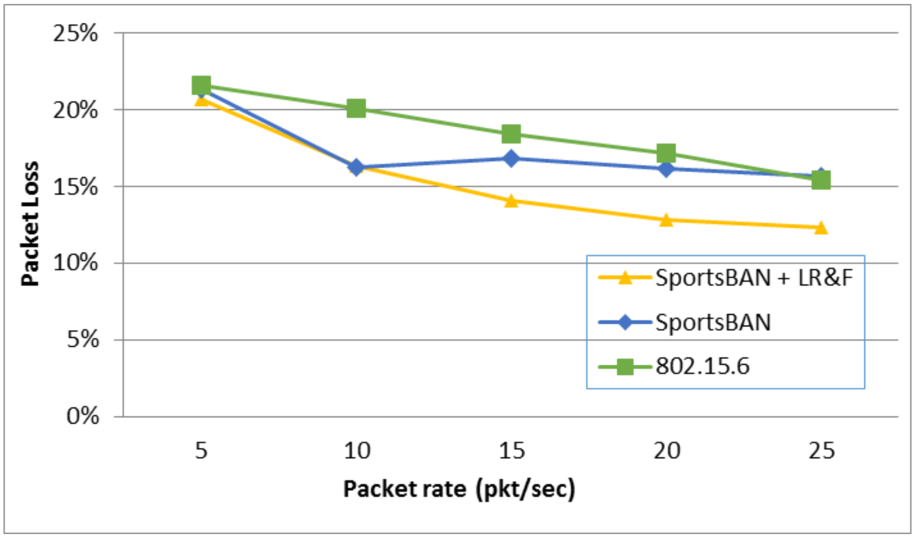

Figure 4.5. Packet loss with emergency traffic vs Packet rate

The Energy Waste Index without emergency traffic, when the packet rate is changed in the WBAN, is depicted in Figure 4.6. The Energy Waste Index for the SportsBAN MAC protocol along with the proposed transport protocol (LR&F) was lower than five for almost all packet rates (except for the initial rate of 5pkt/sec). The proposed transport protocol showed the best energy effectiveness without emergency traffic because although it consumed almost the same quantity of energy as SportsBAN MAC protocol and the IEEE 802.15.6 standard, its percentage of the packet loss was much better. Although the energy consumption for the SportsBAN MAC protocol along with the proposed transport protocol (LR&F) with no emergency traffic could be a little higher due to the lost packets retransmission algorithm, the improvement in the packet loss allows to offer the best energy effectiveness. With the increase of the normal packet rate, the good behavior of the percentage of lost packets and almost the same energy consumption, show the improvement of the proposed transport protocol (LR&F) in the energy effectiveness of the WBAN without emergency traffic.

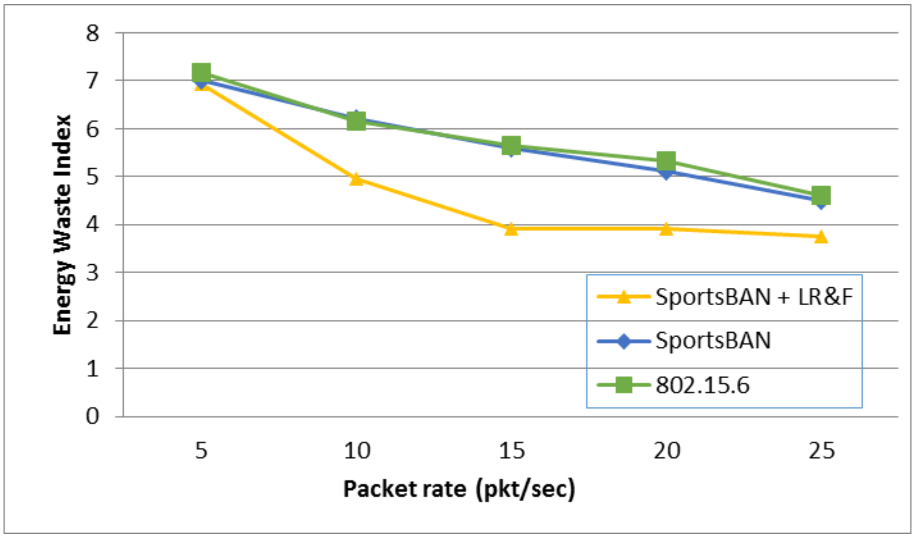

Figure 4.6. Energy Waste Index without emergency traffic vs Packet rate

The Energy Waste Index with emergency traffic, when the packet rate is changed in the WBAN, is depicted in the Figure 4.7. Again, the SportsBAN MAC protocol along with the proposed transport protocol (LR&F) showed the best energy effectiveness with emergency traffic because although it consumed almost the same quantity of energy as SportsBAN MAC protocol and the IEEE 802.15.6 standard, its percentage of the packet loss was much better. Although the energy consumption for the SportsBAN MAC protocol along with the proposed transport protocol (LR&F) with emergency traffic could be a little higher due to the lost packets retransmission algorithm, the improvement in the packet loss allows to offer the best energy effectiveness. With the increase of the normal and emergency packet rate, the good behavior of the percentage of lost packets and almost the same energy consumption, show the improvement of the proposed transport protocol (LR&F) in the energy effectiveness of the WBAN with emergency traffic.

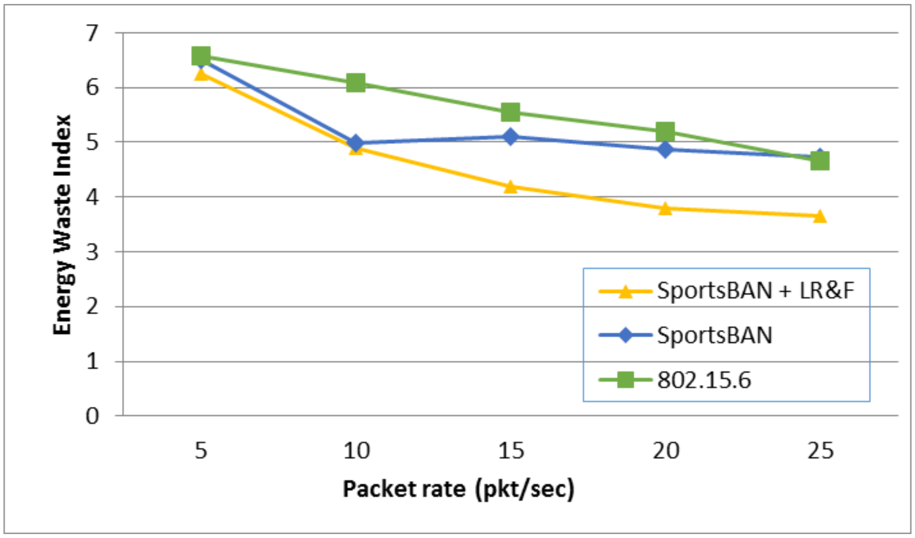

Figure 4.7. Energy Waste Index with emergency traffic vs Packet rate

For the study of the normal and emergency traffic latency, a different simulation was made. The time simulation was 300s, the number of nodes was six and the packet rate was 20pkt/sec. There was only one emergency event occurring at 150s during 5s in one specific sensor node. The Figure 4.8 depicts the distribution of the latency for normal traffic. The total number of normal packets with low latency ([0, 120) ms) shown by the SportsBAN MAC protocol along with the proposed transport protocol was higher than the other two protocols. SportsBAN MAC protocol working alone also offered more total number of packets with low latency ([0, 120) ms) than the IEEE 802.15.6 standard. There is an important number of normal packets delivered with high latency ([160,inf) ms) due to the time each sensor needs to wait to receive the next beacon and listen to the lost normal packet retransmission requests from the hub during the SRP phase.

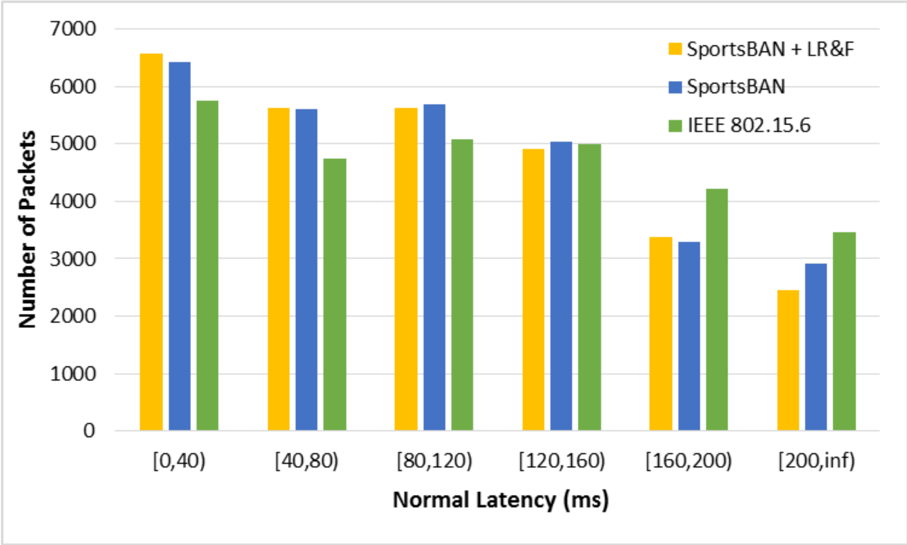

Figure 4.8. Normal Latency for SportsBAN + LR&F

The Figure 4.9 depicts the distribution of latency for emergency traffic in the WBAN. This time, the total number of emergency packets with low latency ([0, 200) ms) shown by the SportsBAN MAC protocol along with the proposed transport protocol (LR&F) was a little lower than the other two protocols. Nonetheless, there is a trade-off between this latency and the total number of received emergency packets, which is higher in the SportsBAN MAC protocol along with the proposed transport protocol (LR&F). The latency behavior of the proposed solution and some emergency packets delivered with high latency ([200,inf) ms) are due to the time each sensor needs to buffer the emergency lost packets and wait to receive the next beacon. Then, the node needs to listen to the lost emergency packet retransmission requests from the hub during the SRP phase and finally send the emergency lost packets requested and previously detected.

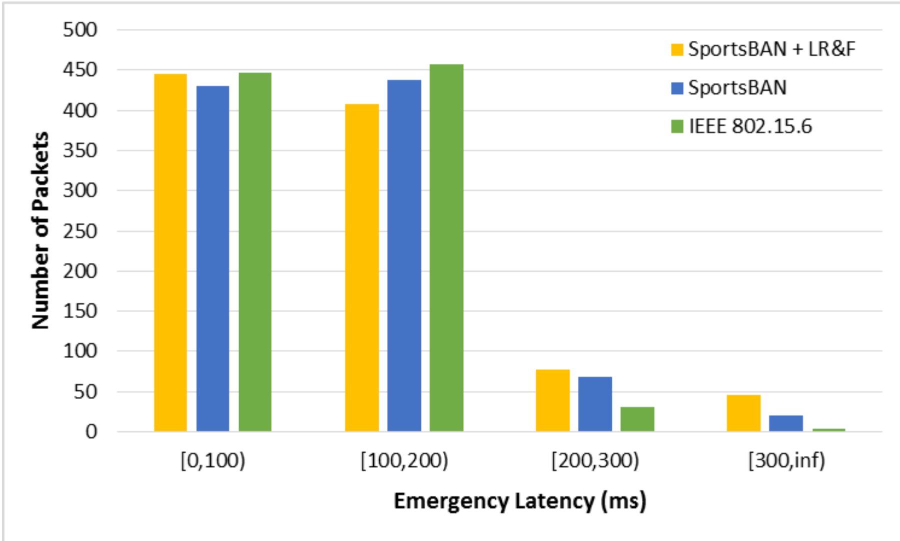

Figure 4.9. Emergency Latency for SportsBAN + LR&F

4.4 Conclusions

In this section, a new transport protocol for WBAN was proposed, based on the implementation of the SportsBAN MAC protocol presented in Chapter 3. The hub and each node in the WBAN detect lost packets and make the requests and retransmissions during the Slot Reallocation Phase (SRP, in the SportsBAN). The hub calculates the Fairness Index as the ratio between the number of lost packets and the total number of received packets. The hub uses the Fairness Index to prioritize the request creation in order to provide fairness between all the nodes in the WBAN.

The SportsBAN MAC protocol along with the proposed transport protocol (LR&F) outperformed the MAC protocol and the IEEE 802.15.6 standard in the percentage of the packet loss with or without emergency traffic, while maintaining a similar energy consumption as both protocols. When the Energy Waste Index was calculated, it showed that the SportsBAN MAC protocol along with the proposed transport protocol (LR&F) had a better energy effectiveness than the other protocols with or without emergency traffic.

Finally, the latency for normal and emergency traffic in the presence of one emergency event was compared. The SportsBAN MAC protocol along with the proposed transport protocol (LR&F) showed a very good latency for normal traffic. The latency for emergency traffic was a little higher than the other two protocols, but showing more reliability with less lost packet.

CHAPTER 5 RATE CONTROL SCHEME FOR CONGESTION CONTROL IN SPORTS WIRELESS BODY AREA NETWORKS

This chapter presents a rate control scheme for mitigating congestion in WBANs used in sports applications. In the section 5.1, the proposed rate control scheme is presented with its congestion control technique. The rate control scheme is context-aware and responses to emergency events in any node controlling the normal traffic rate of the remaining nodes. The section 5.2 presents the simulation results comparing the performance of the IEEE 802.15.6 standard and the SportsBAN MAC protocol when they are used along with the proposed rate control scheme.

5.1 Proposed Rate Control Scheme

The proposed rate control scheme is context-aware and it uses a RIB (Rate-control Indicator Bit) in each beacon for providing congestion avoidance during emergency events. When an emergency event occurs in the WBAN, the hub has to calculate the Rate Control Factor (RCF) and communicate it to all nodes in the network in order to keep the same average rate of traffic during all the emergency event. The hub uses the SRP phase with the TDMA protocol to send the RCF to all nodes. In this way, it avoids contention. When an emergency event happens into any node, the node sends an alert into the application packet to indicate in advance the increase in the packet rate for the emergency node. The emergency packet rate is increased with an Emergency Multiplication Factor (EMF=10 for the simulations).

5.1.1 Node and Hub States

The Figure 5.1 depicts the node states for the SportsBAN MAC protocol working along with the proposed rate control scheme. After receiving a beacon, the node reads the Rate-control Indicator Bit (RIB) and it has to decide if it goes to sleep mode or it listens to the Rate Control Factor sent by the hub during the SRP phase. The node apply immediately the Rate Control Factor, and in this way it reduces its normal packet rate. Then, it will be able to send emergency and normal traffic during the MAP phase and additional emergency and normal traffic during the SCAP phase.

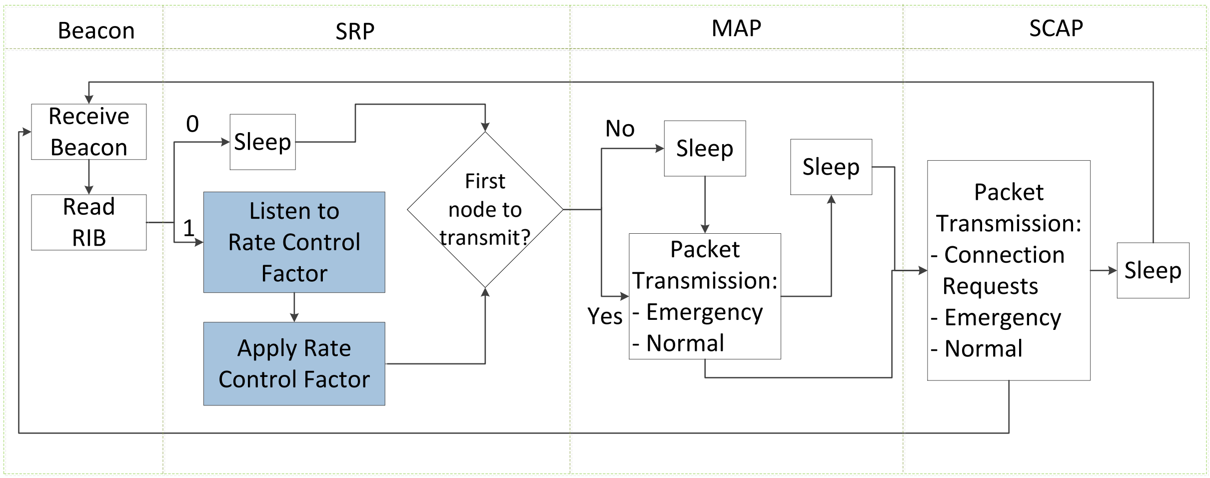

Figure 5.1. Node states in SportsBAN + RCS

The Figure 5.2 depicts the hub states for the SportsBAN MAC protocol working along with the proposed rate control scheme. After sending a beacon, the hub can go to idle mode or it can send the Rate Control Factor to all normal nodes (with no emergency events). The hub uses the TDMA protocol for using all slots during the SRP phase, avoiding contention with the sensor nodes. After sending the Rate Control Factor to all nodes, the hub can go to idle mode during the SRP phase or start to listen to emergency and normal traffic during the MAP phase. Finally, the hub will be listening to additional emergency and normal traffic from connected nodes, listening to connection requests from unconnected nodes, and sending connection assignments.

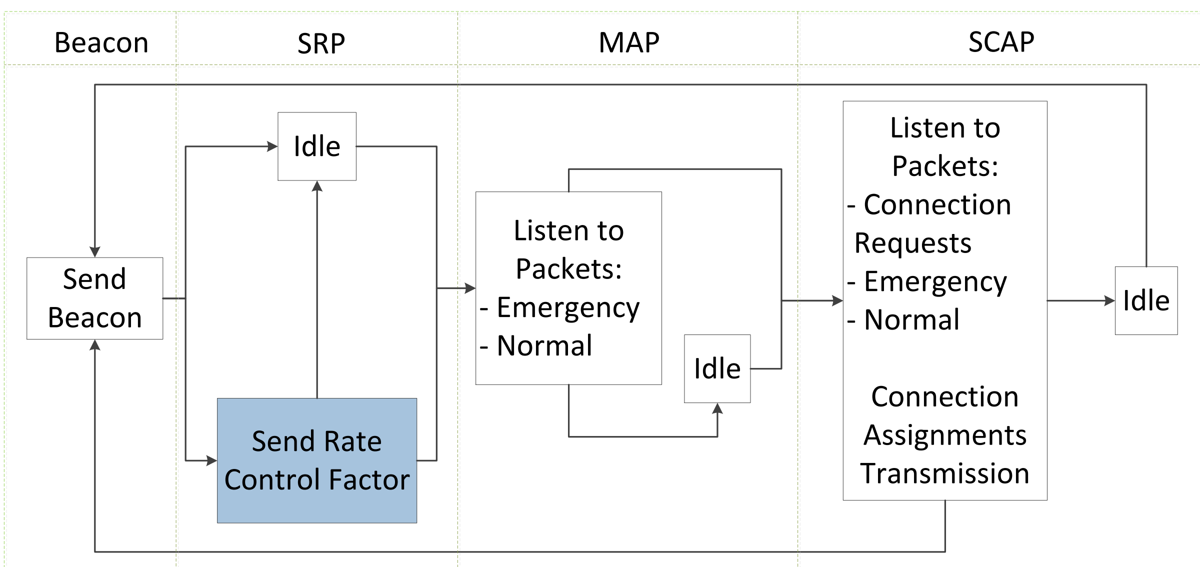

Figure 5.2. Hub states in SportsBAN + RCS

5.1.2 Congestion Control

The Algorithm 5.1 depicts the congestion control scheme used by the hub. When a packet arrives with an alert of future buffer overflow (BUFFER_ALERT) due to an emergency event that happens in any node, the hub calculates the Rate Control Factor (RCF). This factor is a float number between zero and one in order to decrease the packet rate of nodes with normal traffic. The Rate Control Factor is used for keeping almost the same average packet rate in the network, decreasing the packet rate of normal traffic in all nodes and allowing the current nodes with emergency events to use more bandwidth in the WBAN. All the rate control requests are sent by the hub during the SRP phase. As the SRP phase is a non-contention phase due to the TDMA protocol, there is no packet collision during this phase.

ALGORITHM 5.1. Congestion control in the hub

```
If packet.alert = BUFFER_ALERT then
  EmergencyNodes.push(currentNode);
  Calculate RCF for all nodes according to expression (5.3)
  For each node n do
    If n is not in EmergencyNodes then
      Create a Rate Control Request for the node n using RCF
    End If
  End For each
  Set RIB ← Rate Control
End If
Send Rate Control Requests in next SRP
```

The proposed rate control scheme decreases the probability of contention of emergency traffic because the increase of emergency traffic in any node is counteracted with the reduction of normal traffic in the remaining nodes. Besides, it also decreases the probability of the packet loss due to buffer overflow of normal traffic in each node.

When the emergency event finishes, the hub sends another Rate-control Indicator Bit into the next beacon, in order to reassign the original packet rate to each node in the WBAN. The expressions (5.1) and (5.2) depict the average packet rate for the whole WBAN with no emergency traffic ($\bar{r}$) and with emergency traffic ($\overline{r_e}$), respectively.

$$\bar{r} = \frac{\sum_{i=1}^{n} r_i}{n} \tag{5.1}$$

$$\overline{r_e} = \frac{\sum_{j \in n_e}(r_j \times m_j) + \sum_{i=1}^{n} r_i - \sum_{j \in n_e} r_j}{n} \tag{5.2}$$

Where r is the packet rate for each node, n is the total number of nodes in the WBAN, n_e is the set of the current emergency nodes (they might be more than one), and m is the Emergency Multiplication Factor (EMF) for each emergency node.

Using the expressions (5.1) and (5.2), the Rate Control Factor (RCF) for emergency events can be calculated as shown in the expression (5.3) and it must always be $0 < RCF < 1$ in order to decrease the packet rate in the nodes with normal traffic.

$$RCF = \frac{\sum_{i=1}^{n} r_i - \sum_{j \in n_e}(r_j \times m_j)}{\sum_{i=1}^{n} r_i - \sum_{j \in n_e} r_j} \tag{5.3}$$

5.2 Experimental Results

5.2.1 Simulation Parameters

Six nodes composed the simulated network: five sensor nodes and one hub. The sensor in the center is the hub and it is assumed to never go to sleeping mode. It rather goes to idle mode. The Figure 5.3 shows the star topology for the simulated network.

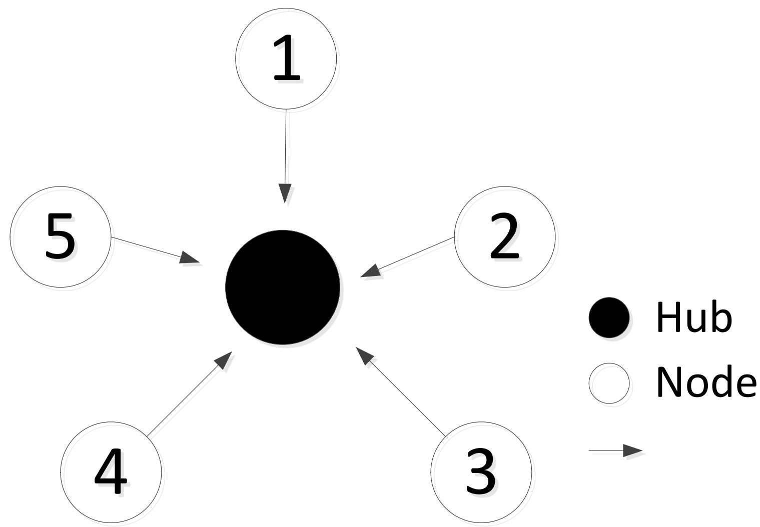

Figure 5.3. Star topology for the simulation scenario of SportsBAN + RCS

The simulation time was always 300s and the normal packet rate was 20pkt/sec. When an emergency event happened in a node, the Emergency Multiplication Factor (EMF) increased the rate in 10 (ten) times, giving an emergency packet rate of 200pkt/sec. The additional simulation parameters for the application, MAC and physical layers are listed in the Table 5.1. The beacon period length was 32 slots for both the IEEE 802.15.6 Standard and SpotsBAN MAC protocol. The MAP length was 26 slots for both the IEEE 802.15.6 Standard and SportsBAN MAC protocol. The remaining six slots were distributed between EAP (three slots) and RAP (three slots) phases for the IEEE 802.15.6 Standard, and between SRP (three slots) and SCAP (three slots) phases for SportsBAN MAC protocol. The values for the parameters: allocation slot length, beacon period length, maximum transmission tries, and normal buffer size were the same in both protocols in order to keep fairness in the comparison.

Table 5.1. Simulation Parameters for SportsBAN + RCS

Layer	Parameter	Value
Application	Packet rate (pkt/sec)	20
	Default Priority for nodes	2
	Constant Data Payload (in bytes)	80
	Emergency Multiplication Factor	10
MAC	Maximum Transmission Tries	2
	Normal Buffer size (packets)	32
	Emergency Buffer size (packets)	32
	Allocation Slot Length (ms)	10
	Beacon Period Length (slots)	32

Layer	Parameter	Value
	SRP Length (slots)	3
	MAP Length (slots)	26
	SCP Length (slots)	3
	Scheduled Access Length (slots)	2
	Scheduled Access Period	1
	Contention Slot Length (ms)	0.36
Physical	Topology	Star
	Sensors	5
	Hubs	1
	TX Output Power (dBm)	-10
	Baseline Node Power (mW)	10

5.2.2 Simulation Results

The first variable used for the comparison of the IEEE 802.15.6 standard and the SportsBAN MAC protocol working along with the proposed rate control scheme was the percentage of emergency packet loss. The second variable used for the comparison was the Energy Waste Index. The latter was calculated as the ratio between the percentage of the packet loss and the average consumed energy. The lower its value the better the effectiveness of the solution.

The comparison of the simulations were made among: (i) the IEEE 802.15.6 standard without the rate control scheme (RCS); (ii) the IEEE 802.15.6 standard using a part of the proposed rate control scheme; (iii) the SportsBAN MAC protocol proposed in Chapter 3 without the rate control scheme; and (iv) the SportsBAN MAC protocol using the proposed rate control scheme.

The percentage of emergency packet loss when the number of emergency events were changed from one to five during simulations is depicted in Figure 5.4. The proposed rate control scheme improved the performance of both IEEE 802.15.6 standard and the SportsBAN MAC protocol. Although the difference between the SportsBAN MAC protocol with and without the rate control scheme is very small in the Figure 5.4, the Energy Waste Index in the Figure 5.5 showed the actual improvement. The proposed rate control scheme allowed the node with emergency events to use more bandwidth, decreasing the rate of the remaining nodes with normal traffic and improving the energy efficiency of the WBAN. The Rate Control Factor calculated with the expression (5.3) was used by the hub allowing to keep the same average packet rate in the WBAN and decreasing the probability of the emergency packet loss due to packet collision and buffer overflow (emergency and normal). The proposed solution (SportsBAN + RCS) showed the best percentage of emergency packet loss compared with the IEEE 802.15.6 standard and the SportsBAN MAC protocol working alone.

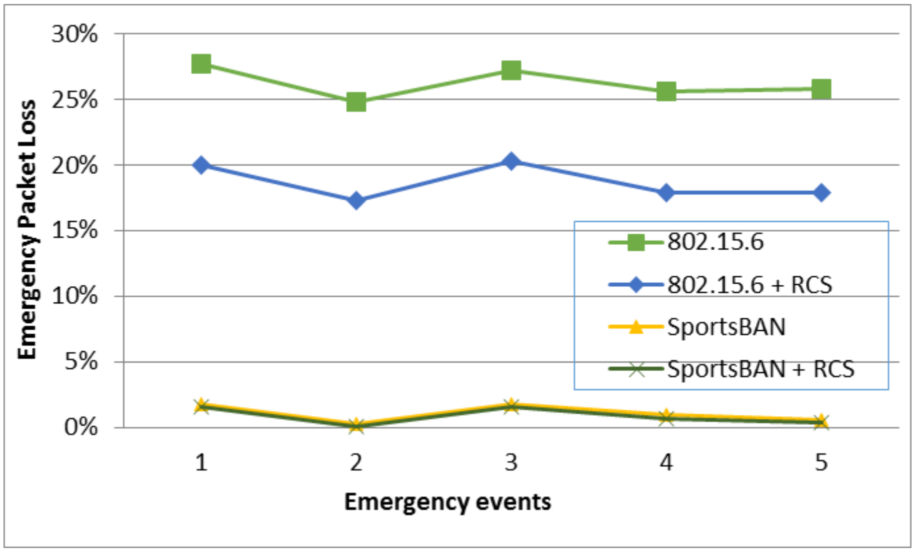

Figure 5.4. Emergency packet loss vs # emergency events

The Energy Waste Index when the number of emergency events were changed from one to five during simulations is depicted in Figure 5.5. Only the SportsBAN MAC protocol with and without the rate control scheme is shown because the difference with the IEEE 802.15.6 is evident in the Figure 5.4. The proposed rate control scheme improved the energy effectiveness of the SportsBAN MAC protocol. This could be accomplished with both the reduction in the emergency packet loss due to the packet collision and the reduction in the normal packet loss due to buffer overflow. With low emergency packet collisions and low emergency buffer overflow, the energy effectiveness of the SportsBAN MAC protocol working along with the Rate Control Scheme (RCS) was better than both the SportsBAN MAC protocol working alone and the IEEE 802.15.6 standard.

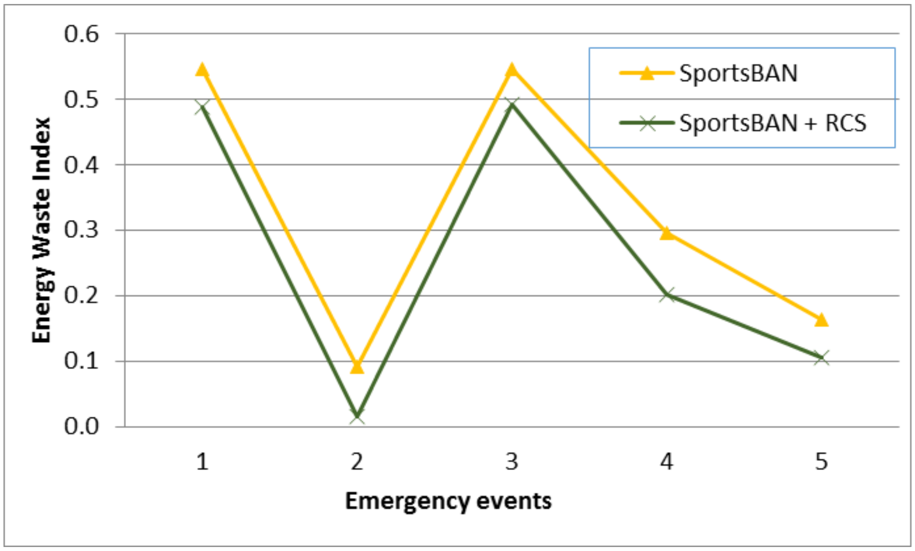

Figure 5.5. Energy Waste Index vs # emergency events

The emergency packet loss when a given number of simultaneous emergency events (from one to four) happened during the simulations is depicted in the Figure 5.6. The emergency nodes had simultaneous emergency events three times during the simulations (at 80s, 160s and 240s). It can be seen that the rate control scheme improved again the performance of both the IEEE 802.15.6 standard and the SportsBAN MAC protocol. The proposed rate control scheme decreases the packet rate of the remaining nodes with normal traffic in order to provide emergency-awareness to the whole WBAN. With the increase of emergency nodes sending emergency traffic at the same time, the Rate Control Scheme allowed to keep the same average packet rate than the WBAN with no emergency traffic. The proposed solution (SportsBAN + RCS) showed the best percentage of emergency packet loss compared with the IEEE 802.15.6 standard and the SportsBAN MAC protocol working alone.

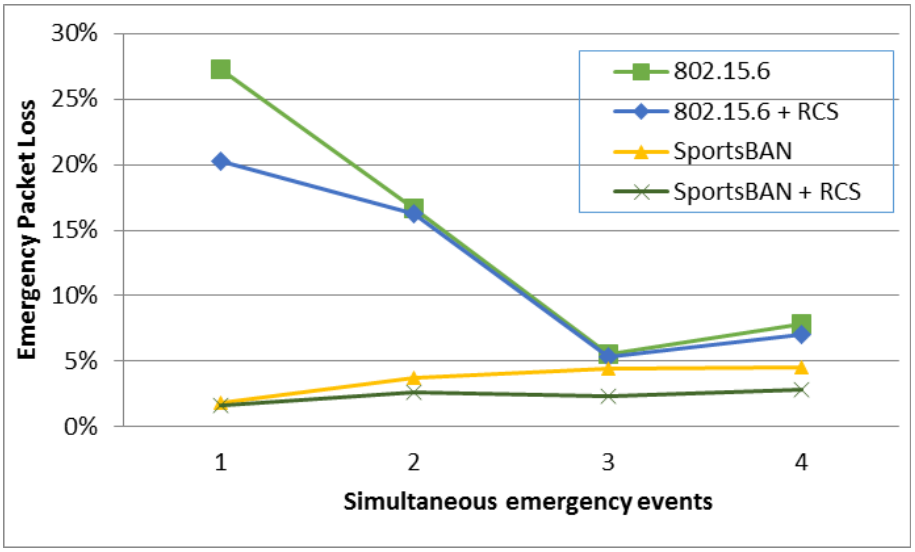

Figure 5.6. Emergency packet loss vs # simultaneous emergency events

The Energy Waste Index when a given number of simultaneous emergency events (from one to four) happened during the simulation is depicted in the Figure 5.7. Only the SportsBAN MAC protocol with and without the rate control scheme is shown because the difference with the IEEE 802.15.6 is evident in the Figure 5.6. The proposed rate control scheme improved the energy effectiveness of the SportsBAN MAC protocol. This could be accomplished with both the reduction in the emergency packet loss due to the packet collision and the reduction in the normal packet loss due to buffer overflow. The energy effectiveness was better as the number of simultaneous emergency events increased. With the increase of emergency nodes sending emergency traffic at the same time, the Rate Control Scheme allowed to keep the same average packet rate than the WBAN with no emergency traffic. The energy effectiveness of the proposed solution (SportsBAN + RCS) is due to the best percentage of emergency packet loss and the use of free-contention transmission of the request lost packets, in order to keep a good energy consumption.

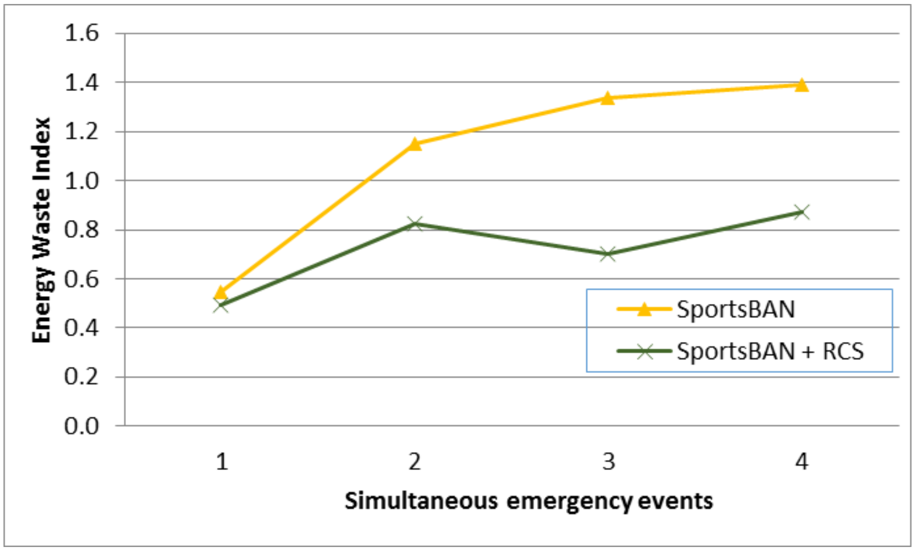

Figure 5.7. Energy Waste Index vs # simultaneous emergency events

For the third simulation, the packet rate was 20pkt/sec, the simulation time was 300s and there was one emergency node in the WBAN. The Figure 5.8 depicts the total number of lost packets (normal and emergency traffic) due to buffer overflow or busy channel. The proposed rate control scheme improved the performance of both IEEE 802.15.6 standard and the SportsBAN MAC protocol. Although the difference between the SportsBAN MAC protocol with and without the rate control scheme is very small in the Figure 5.8, the Energy Waste Index in the Figure 5.9 showed the actual improvement. The proposed rate control scheme decreases both the normal packet loss due to buffer overflow and the emergency packet loss due to a busy channel. This Rate Control Scheme improves the total number of lost packets (normal and emergency) because it also decreases the packet collision probability in the WBAN. Each nodes can buffer normal and emergency detected lost packets and these packets can be sent during SRP with no contention after being requested from the hub.

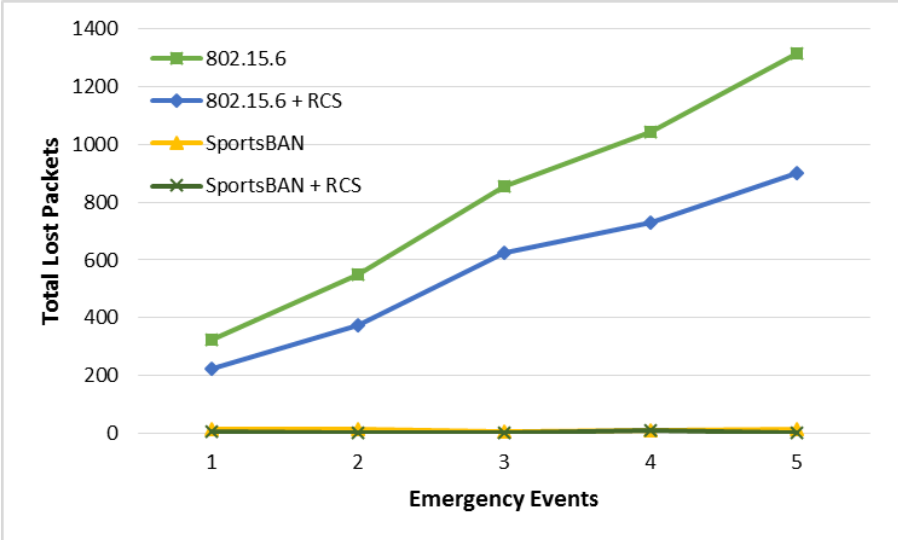

Figure 5.8. Total Lost Packets vs. Emergency Events

The Figure 5.9 depicts the difference between the SportsBAN MAC protocol working along with the proposed rate control scheme and without its use. It shows the total number of lost packets due to buffer overflow or busy channel. The proposed rate control scheme improves the already good performance of the SportsBAN MAC protocol with the packet loss. This Rate Control Scheme improves the total number of lost packets because it also decreases the packet collision probability in the WBAN. Each nodes can buffer normal and emergency detected lost packets and these packets can be sent during SRP with no contention after being requested from the hub.

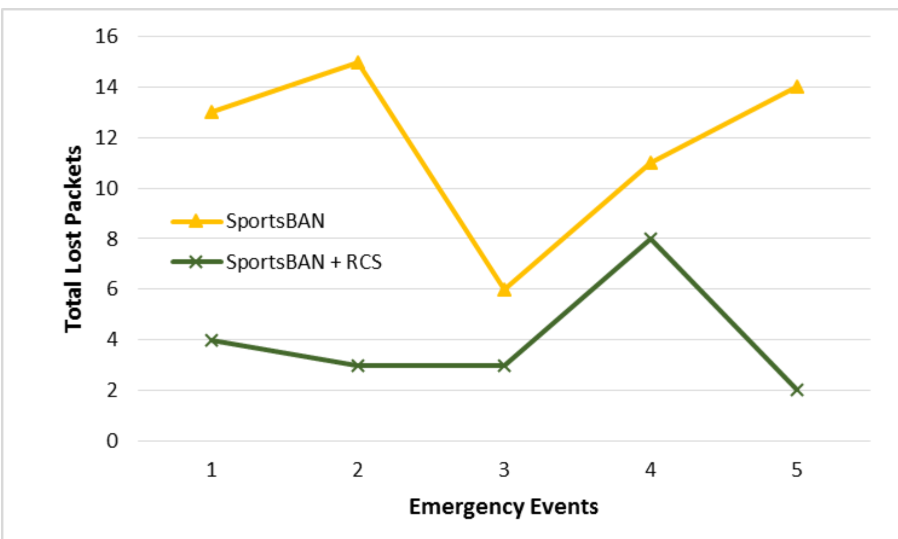

Figure 5.9. Total Lost Packets vs. Emergency Events for SportsBAN + RCS

For the fourth simulation, the packet rate was 20pkt/sec, the simulation time was 300s and there were no emergency nodes in the WBAN. The Figure 5.10 depicts the distribution of the latency for normal traffic. The total number of normal packets with low latency ([0, 160) ms) shown by the SportsBAN MAC protocol along with the proposed rate control scheme (RCS) was very good compared with the other solutions. We need to consider a trade-off between the good normal traffic latency depicted in the Figure 5.10, and the excellent emergency traffic latency depicted in the Figure 5.11. Besides, the total number of normal transmitted packets is fewer in the proposed solution (SportsBAN + RCS) than the other three solutions because the hub has previously requested the decrease in the normal packet rate.

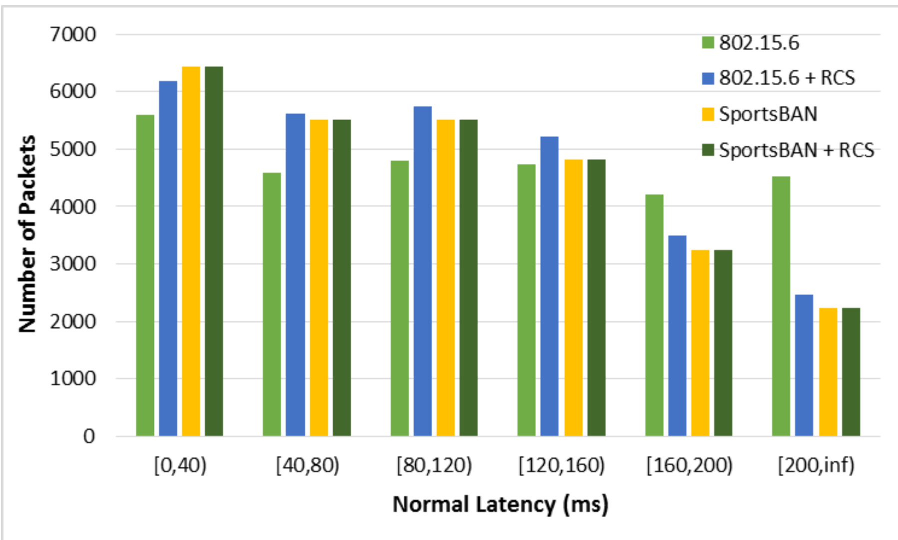

Figure 5.10. Normal Latency for SportsBAN + RCS

For the final simulation, the packet rate was 25pkt/sec, the simulation time was 300s and there was one emergency node in the WBAN. The Figure 5.11 depicts the distribution of the latency for emergency traffic. The total number of emergency packets with low latency ([0, 200) ms) shown by the SportsBAN MAC protocol along with the proposed rate control scheme (RCS) was higher than the other solutions. This is due to the priority of emergency packets in the SportsBAN MAC protocol and the decrease of normal traffic with the proposed rate control scheme. SportsBAN MAC protocol gives more priority to emergency traffic during the MAP phase offering a free-contention transmission. Besides, the RCS improve the SportsBAN behavior because decreases the normal traffic, allowing more emergency traffic to be sent during MAP.

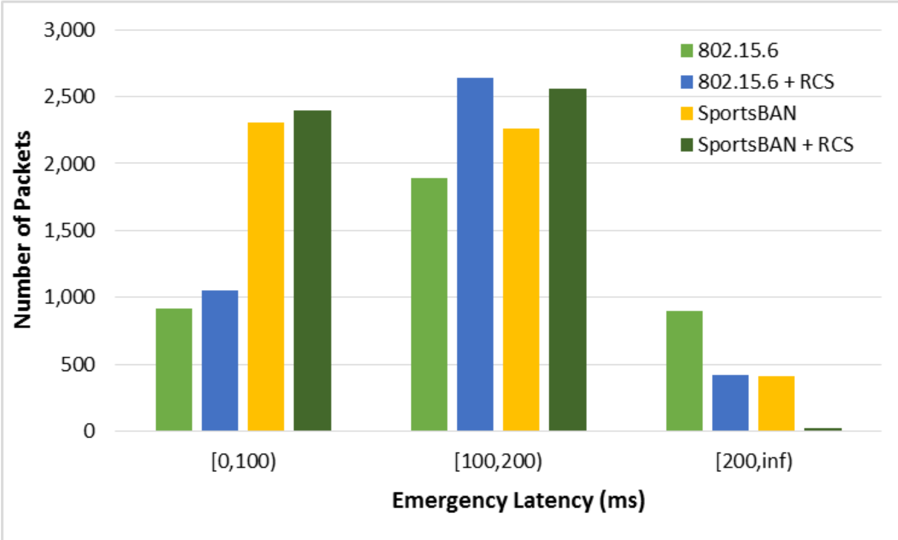

Figure 5.11. Emergency Latency for SportsBAN + RCS

5.3 Conclusions

A new context-aware rate control scheme for congestion control in Wireless Body Area Networks was proposed in this chapter, based on the emergency-aware and energy-efficient MAC protocol presented in Chapter 3. The hub calculates a Rate Control Factor (RCF) each time an emergency event happens in any node of the network. It sends the RCF to decrease the packet rate in nodes with normal traffic and to keep almost the same average packet rate in the whole WBAN. The RCF is sent during the SRP phase to all normal nodes. In this way, the hub avoids contention and packet collision.

For evaluating the performance of the proposed rate control scheme, four variables were used: the percentage of emergency packet loss, the Energy Waste Index (calculated as the ratio between the percentage of the emergency packet loss and the average consumed energy), the total number of lost packets (normal and emergency traffic) due to buffer overflow or busy channel, and the latency for emergency and normal traffic. The proposed rate control scheme improved the performance of both the SportsBAN MAC protocol and the IEEE 802.15.6 standard.

CHAPTER 6 PROPOSED ARCHITECTURE

The proposed architecture gathers all the protocols and schemes presented in this research project and it is explained in this chapter. The section 6.1 poses the initial assumptions. The section 6.2 enumerates its requirements. The section 6.3 explains the proposed topologies: WBAN topology and global topology. The section 6.4 explains the operation of the R's Indicator Bits scheme for each beacon period. The section 6.5 presents the proposed phases for each beacon period. The section 6.6 summarizes all the tackled challenges, and the proposed protocols and schemes. The section 6.7 explains the node behavior. The section 6.8 presents a comparison with other proposed architectures using the main requirements. Finally, the section 6.9 concludes the chapter.

The main objective of this research project was to design a reliable, context-aware and energy-efficient architecture for WBANs, ensuring QoS and fairness in sports applications. This objective was achieved through the proposed protocols, algorithms, schemes, and the proposition of a new hub and nodes architecture.

The Figure 6.1 depicts the proposed general architecture. The hub and the sensors are composed of five modules: (i) Sensing Module (SM) – in charge of sensing body information and detecting alerts into the packets; (ii) Memory Module (MM) – in charge of storing sensing data and lost packets for future retransmissions; (iii) Battery Module (BM) – in charge of giving energy to all the modules within the device, and detecting low battery levels; (iv) Processing Module (PM) – in charge of processing body information, creation of slot reallocations, detecting lost packets, sending requested lost packets, and processing the Rate Control Factor for congestion control; and (v) Radio-Frequency Module (RFM) – in charge of the transmission of the body information between the nodes and the hub (via HBC, NB, UWB), and between the hub and the coach devices, data centers, and other stakeholders (via GSM, LTE, Wi-Fi, WiMAX).

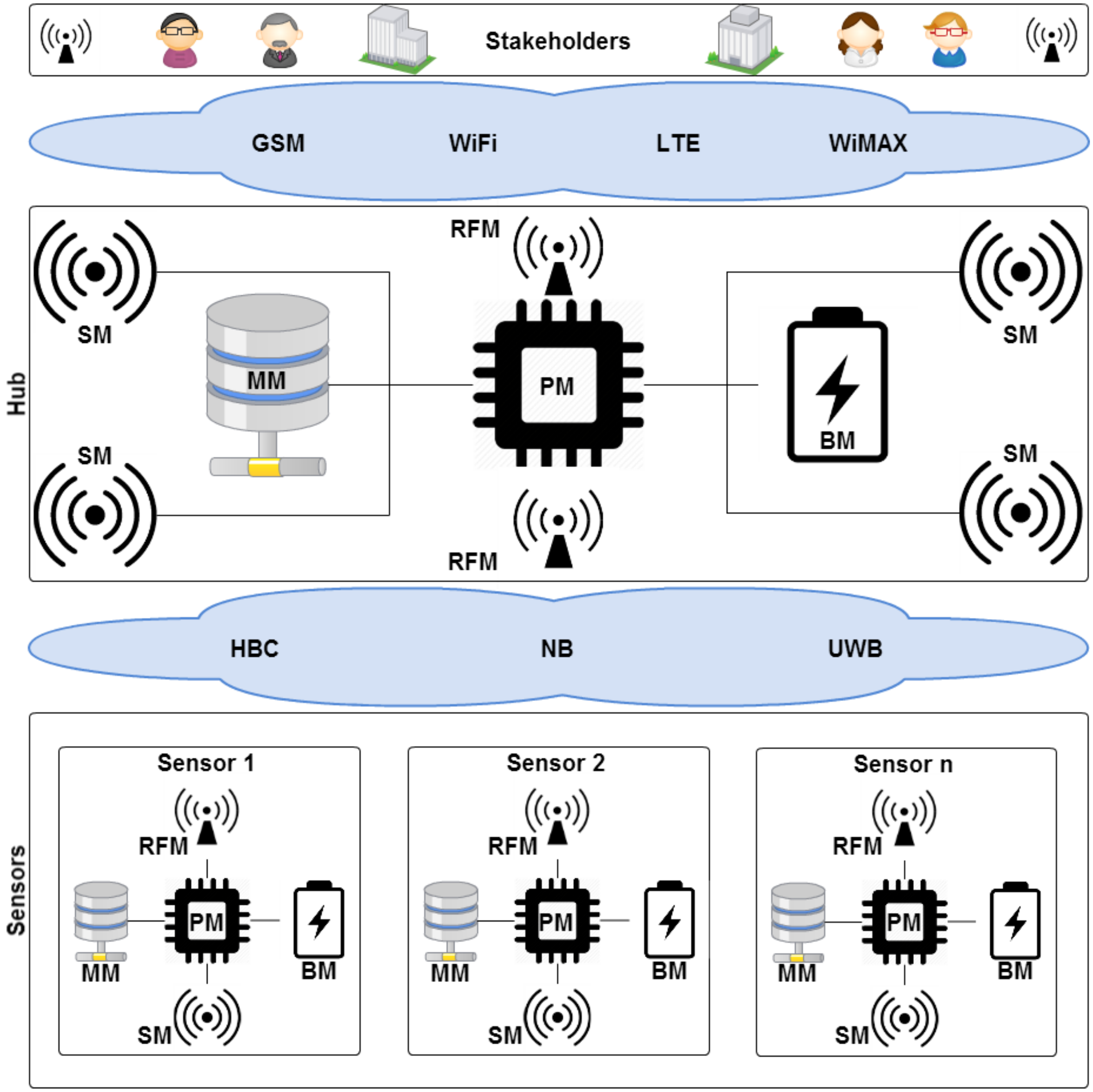

Figure 6.1. Proposed General Architecture

The Figure 6.2 depicts the node architecture with its five modules: (i) The Sensing Module (SM) supports the Slot Reallocation Algorithm with the detection of the alert type into each packet; (ii) The Memory Module (MM) supports the Slot Reallocation Algorithm with the detection of future emergency buffer overflow, and supports the Lost Packet Retransmission Algorithm with the buffering of lost packet for future retransmissions; (iii) The Battery Module (BM) supports the Slot Reallocation Algorithm with the detection of low battery levels; (iv) The Processing Module (PM) supports the Slot Reallocation Algorithm, the Rate Control Scheme with the processing of the Rate Control Factor, and supports both the Packet Loss Detection Algorithm and the Lost Packet Retransmission Algorithm with the creation of lost packet retransmission requests and the sending of lost packet retransmissions; and (v) The Radio-Frequency Module (RFM) supports the Slot Reallocation Algorithm, the Rate Control Scheme and the Packet Loss Detection Algorithm, with the sending of slot reallocations, the RCF, and lost packet retransmissions respectively.

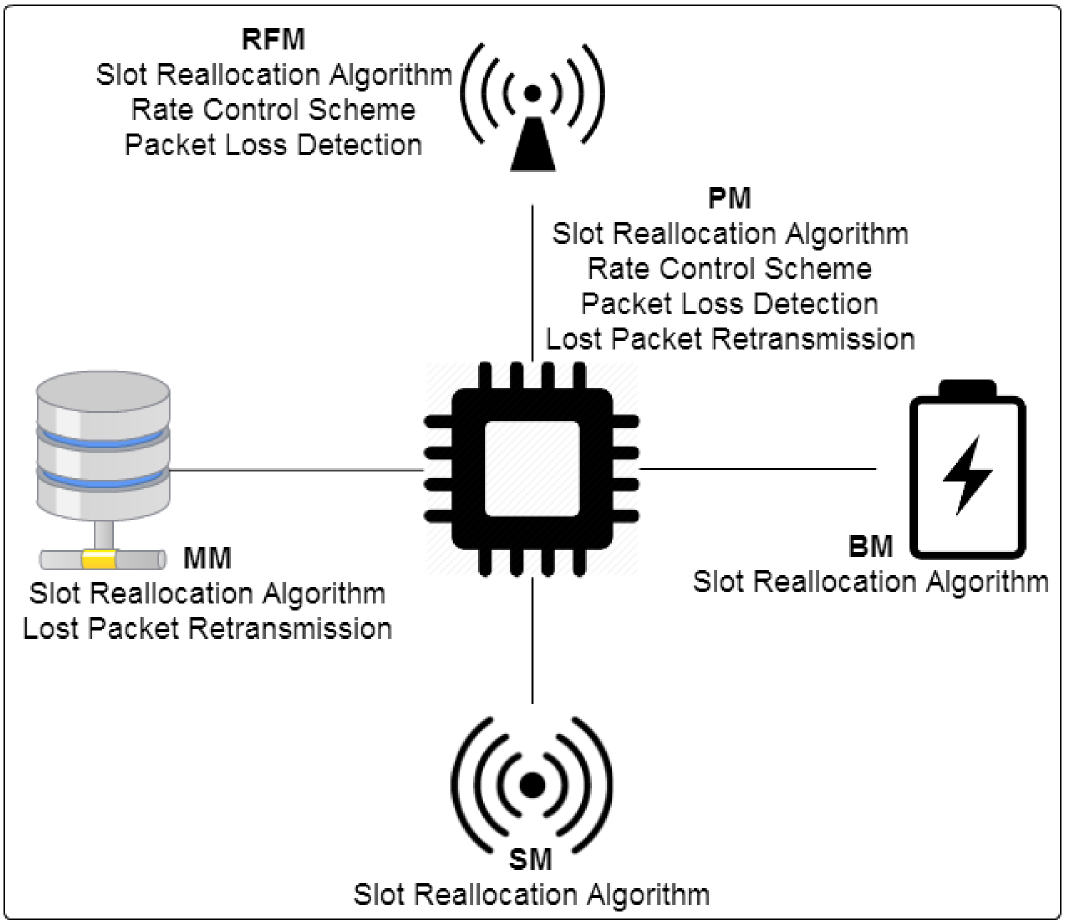

Figure 6.2. Node Architecture

6.1 Assumptions

- We assume that the WBAN is used by sportsmen in good health condition. The sensor nodes and the coordinator are worn by the athletes. The WBAN can help the athletes with scientific training, posture correcting and skill improvement, avoiding them injuries.
- The users of a WBAN could have some inhibitions related to invasiveness and discomfort due to the sensors size or position. The sensor nodes need to be wearable and lightweight and they should not alter the user's normal activities.
- The cost of implementing the proposed solution could be high, but the solution should demonstrate enough value to offset the inversion.
- The proposed solution will depend on sensor accuracy, so, the sensors should be optimally calibrated in order to assure it. Besides, sports applications demand for high-capacity systems to deliver real-time information.
- The hub or WBAN coordinator never sleeps, it is always on and it only goes to idle mode when all nodes are in sleeping mode. The hub’s battery lifetime is much longer than sensor nodes’.
- The hub has enough processing capabilities to perform a multitude of functions like additional sensing, node registration, initialization, customization, secure communication, fusing data from sensor nodes, serving as a user interface and bridging the WBAN to higher-level infrastructure and thus to other stakeholders.

6.2 Requirements

The architecture should provide to the hub and each node within the WBAN with some specific abilities. We can enumerate the main requirements of the proposed architecture like:

- Energy Efficiency: to minimize the power consumption avoiding or mitigating collisions, idle listening, overhearing, and control packet overhead. The proposed architecture should decrease contention-based transmissions and increase the sleeping time for each node.

- Reliability: to assure the end-to-end packet delivery between the sensor nodes and the hub. The proposed architecture should allow the nodes to be able of sending all their emergency and normal packets to the hub.
- QoS: to have the ability to deliver packets with the least latency and the highest throughput. The proposed architecture should allow the trade-off between the energy efficiency and the desired reliability of the WBAN.
- Congestion Control: ability to control traffic in the WBAN in order to avoid packet collision and buffer overflow. The proposed architecture should decrease the packet loss due to the packet collision and buffer (normal and emergency) overflow.
- Rate Control: ability to prevent the nodes from overwhelming the hub. The proposed architecture should allow the hub to control the packet rate of the sensor nodes in order to keep an average rate in the whole WBAN.
- Loss Detection: ability to detect the lost packets in the hub side and in each node side. The proposed architecture should provide the early detection of lost packets on both sides: the hub and the sensor nodes.
- Loss Recovery: ability to make the lost packet retransmission requests and to send the corresponding packet retransmissions. The proposed architecture should decrease the total number of lost packet through the retransmission of some of them.
- Fairness: ability to distribute the network resources equitably among all nodes of the WBAN. The proposed architecture should allow all nodes to get equal access to the network and give the corresponding priority to those nodes with emergency traffic and with high packet rate.
- Emergency Awareness: ability to respond to any emergency event in any node at any time. The proposed architecture should be able to detect early any emergency event and to give the corresponding priority to the emergency nodes.
- Context Awareness: ability to respond to any alert (buffer, battery, emergency) in any node at any time. The proposed architecture should be able to detect high buffer levels, low battery levels, and any emergency event into the nodes.

The correspondence between the requirements of the proposed architecture and the protocols, schemes and algorithms proposed in this research project is depicted in the Table 6.1. Each row indicates what algorithm or scheme addresses each requirement.

Table 6.1. Protocols, schemes and algorithms vs Requirements

Requirement	**Slot Reallocation Algorithm**	**Packet Loss Detection Algorithm**	**Lost Packet Retransmission Request**	**Lost Packet Retransmission Sending**	**Rate Control Scheme**
Energy Efficiency	X				X
Reliability	X	X	X	X	
QoS	X	X	X	X	X
Congestion Control					X
Rate Control					X
Loss Detection		X			
Loss Recovery		X	X	X	
Fairness		X	X	X	X
Emergency Awareness	X				X
Context Awareness	X				

6.3 Topologies

The proposed WBAN topology is always a star topology. In this way, we do not need to use a special routing protocol. The hub (1) must always be in the center. The sensor nodes must be around the hub. A star topology with six nodes is depicted in the Figure 6.3. The hub (1) is in the right hip. There are two sensor nodes over the wrists (2 and 3), two sensor nodes over the ankles (4 and 5) and one last sensor node (6) over the chest. Each sensor node has a direct wireless connection with the hub, and there are not relaying nodes for the packet routing. With this direct connection of sensor nodes to the hub, the information takes the least possible delay in transmission. Besides, the failure of a single node does not compromise the remaining nodes.

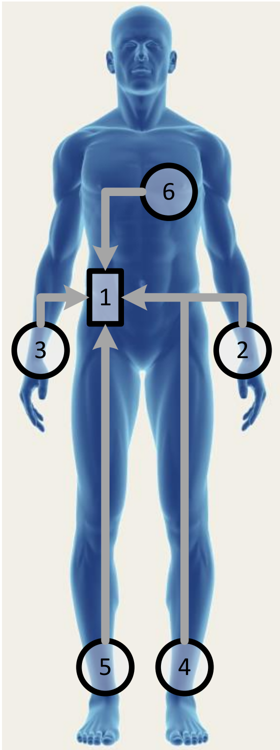

Figure 6.3. WBAN topology in the proposed architecture

The Figure 6.4 depicts the global topology for the proposed architecture. After gathering and processing the body information from nodes within the WBAN star topology, the hub can send this information both directly to a coach device (via Wi-Fi, GSM, LTE) or to other stakeholders (via GSM, LTE, Wi-Fi, WiMAX). The coach device can perform additional processing to help the coach to improve the training plan of the sportsman. The stakeholders can see the processed information into the data centers to improve research in training protocols of athletes, and deficiency detection.

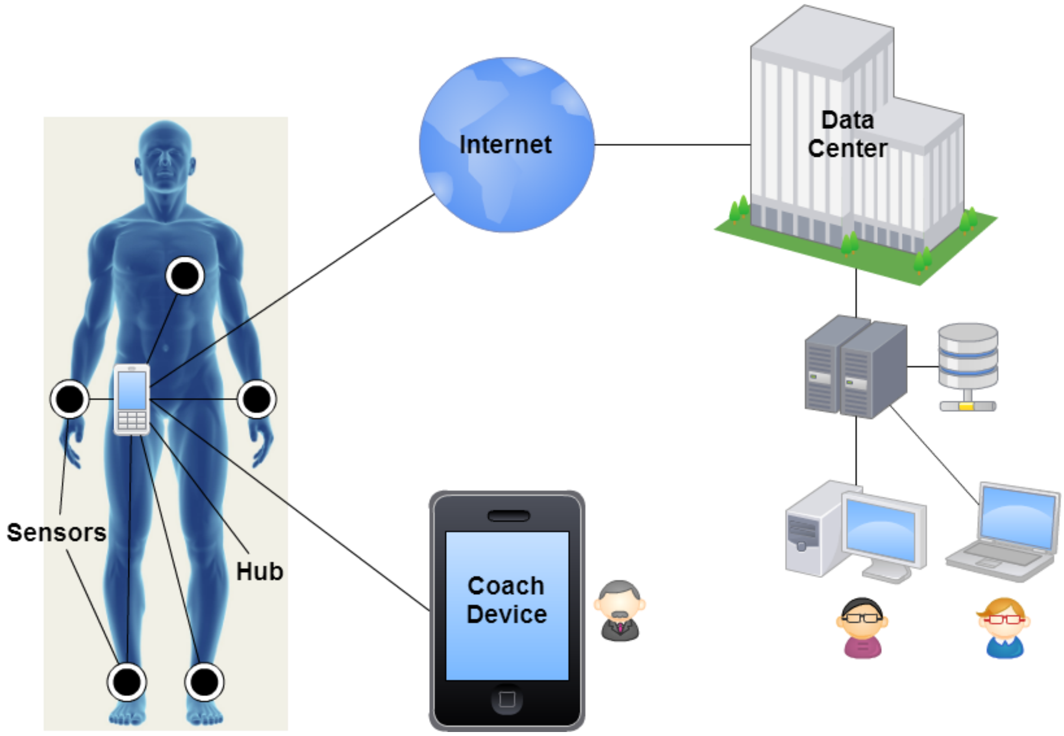

Figure 6.4. Global topology in the proposed architecture

6.4 R's Indicator Bits in the Beacon

The Table 6.2 shows the configuration of indicator bits into each beacon for the proposed architecture. We only use three extra bits within each beacon for indicating whether the hub is going to assign slot Reallocations, to request packet Retransmissions, to send Rate-control requests, or any combination of them. When an emergency event happens in any node, the hub receives an alert from the node and it can decide if the congestion control is necessary and using the Rate-control Indicator Bit. If there are many lost packets detected by the hub, it may use the Retransmission Indicator Bit. The Reallocation Indicator Bit is always used by the hub after an emergency event occurs in any node.

The value 1 (one) in the Reallocation Indicator Bit means that the hub is going to send slot reallocations to all nodes in the current beacon period. The value 1 (one) in the Retransmission Indicator Bit means that the hub has detected lost packets and it is going to send retransmission requests in the current beacon period. The value 1 (one) in the Rate-control Indicator Bit means that the hub has received an emergency alert and it is going to send a Rate-Control Factor to all nodes in the current beacon period.

Table 6.2. Indicator bits for the proposed architecture

Type	First Bit	Second Bit	Third Bit
None	0	0	0
Reallocation	1	0	0
Retransmission	0	1	0
Rate-control	0	0	1
Reallocation & Retransmission	1	1	0
Reallocation & Rate-control	1	0	1
Retransmission & Rate-control	0	1	1
Reallocation, Retransmission & Rate-control	1	1	1

6.5 Phases in the Beacon Period

The Figure 6.5 depicts the three proposed phases within the beacon period. The first phase is called 3RP (Reallocation, Retransmission & Rate-control Phase). 3RP is used by the hub for sending slot reallocations, retransmission requests and the Rate Control Factor (RCF) to all nodes. The second phase is MAP (Managed Access Phase). It is used by all nodes for sending normal an emergency traffic, always giving the highest priority to the emergency traffic. The third phase is called SCAP (Special Contention Access Phase). It is used by all nodes for sending connection requests and additional normal and emergency traffic.

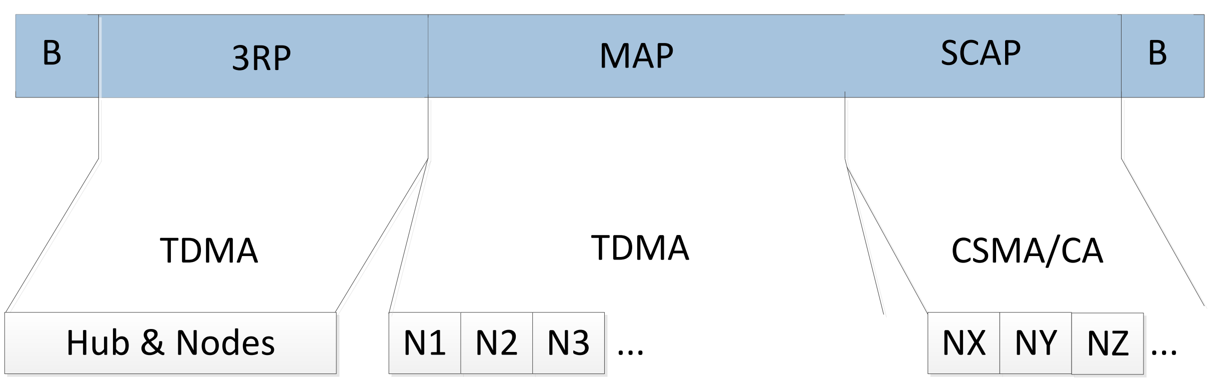

Figure 6.5. Phases in the beacon period for the proposed architecture

There is no contention during 3RP due to the use of the TDMA protocol. The hub uses all slots for sending slot reallocations and the RCF. The nodes only send lost packet retransmissions after they have received a lost packet retransmission request from the hub. MAP also uses the TDMA protocol for transmitting normal and emergency traffic. The use of CSMA/CA in SCAP implies contention-based transmission during this phase. At least one phase needs to offer contention to allow the unconnected nodes to connect to the WBAN.

6.6 Protocols and Schemes

All the challenges tackled can be located within the proposed architecture on the communication protocol stack. The context awareness is provided for the application and MAC layers. The energy efficiency is provided for the transport and MAC layers. The reliability is provided for the transport and MAC layers. The loss recovery, the fairness and the congestion control are provided for the transport layer. The Quality of Service is provided for the MAC layer.

The Figure 6.6 depicts the summary of the proposed architecture with all the communication layers, the protocols and schemes implemented in both the hub and the nodes.

The Packet Loss Detection Algorithm is used by the hub and the nodes. The hub and the nodes detect lost packets in the MAC layer. The hub uses the Lost Packet Retransmission Request Algorithm to request for previous lost packets, while the nodes use the Lost Packet Retransmission Sending Algorithm to send the corresponding lost packets requested by the hub.

The network protocol used by both the hub and the nodes is a simple Bypass protocol. That means there is no special routing in the star topology used in the WBAN. We are using a one-hop star topology, and we are not considering the coexistence of more WBANs in the vicinity.

The Rate Control Scheme is used by the hub in the MAC layer to calculate the RCF for all nodes, while it is used by the nodes in the application layer for applying the received RCF from the hub. The Slot Reallocation Algorithm is only used by the hub in the MAC layer to create the slot reallocations for all nodes.

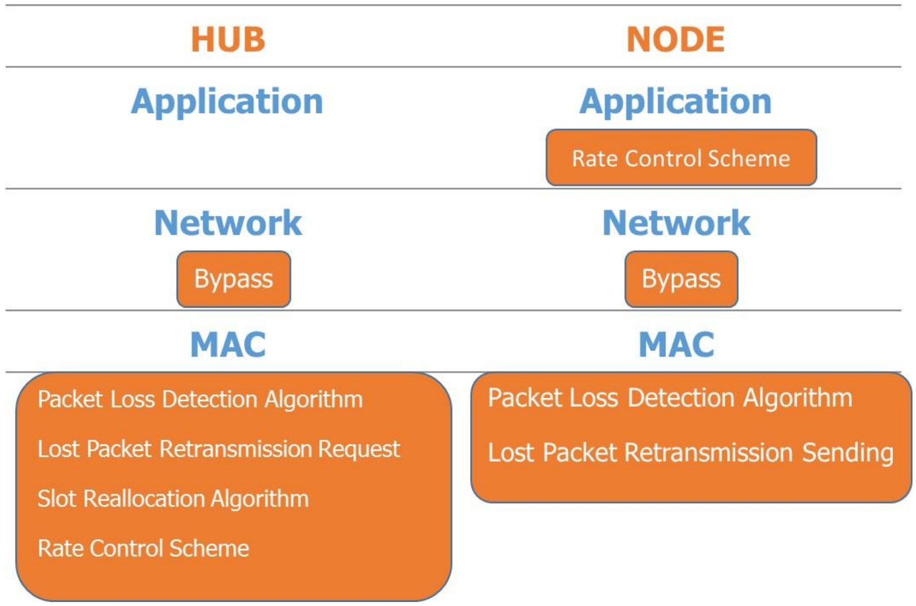

Figure 6.6. Protocols and schemes within the proposed architecture

6.7 Node Behavior

The Figure 6.7 summarizes the behavior of each node for the proposed architecture. After the beacon reception, the node has two options: it evaluates the RIBs if it is connected or it must wait until SCAP if it is unconnected. When it is unconnected, the node will always send its connection request during the next SCAP.

During 3RP (the yellow color zone), the node has previously evaluated the RIBs, then, the node can listen to slot reallocations sent from the hub, or listen to the RCF sent from the hub, or listen to lost packet retransmission requests sent from the hub and finally send the lost packets requested by the hub.

During MAP (the blue color zone), the node sends emergency and normal packets giving the highest priority to the emergency traffic. The node uses its own assigned slots and it might use the remaining slots at the end of MAP if needed. If there were slot reallocations for this beacon period, the node will use the new slot reallocation received, otherwise, it will use the original slot relocation received when it connected to the WBAN for the first time.

Finally, during SCAP (the green color zone), the node sends management packets (e.g. connection requests) and additional emergency and normal traffic. The priority from the highest to the lowest for the traffic during SCAP is: (1) Management packets (2) Emergency traffic and (3) Normal traffic.

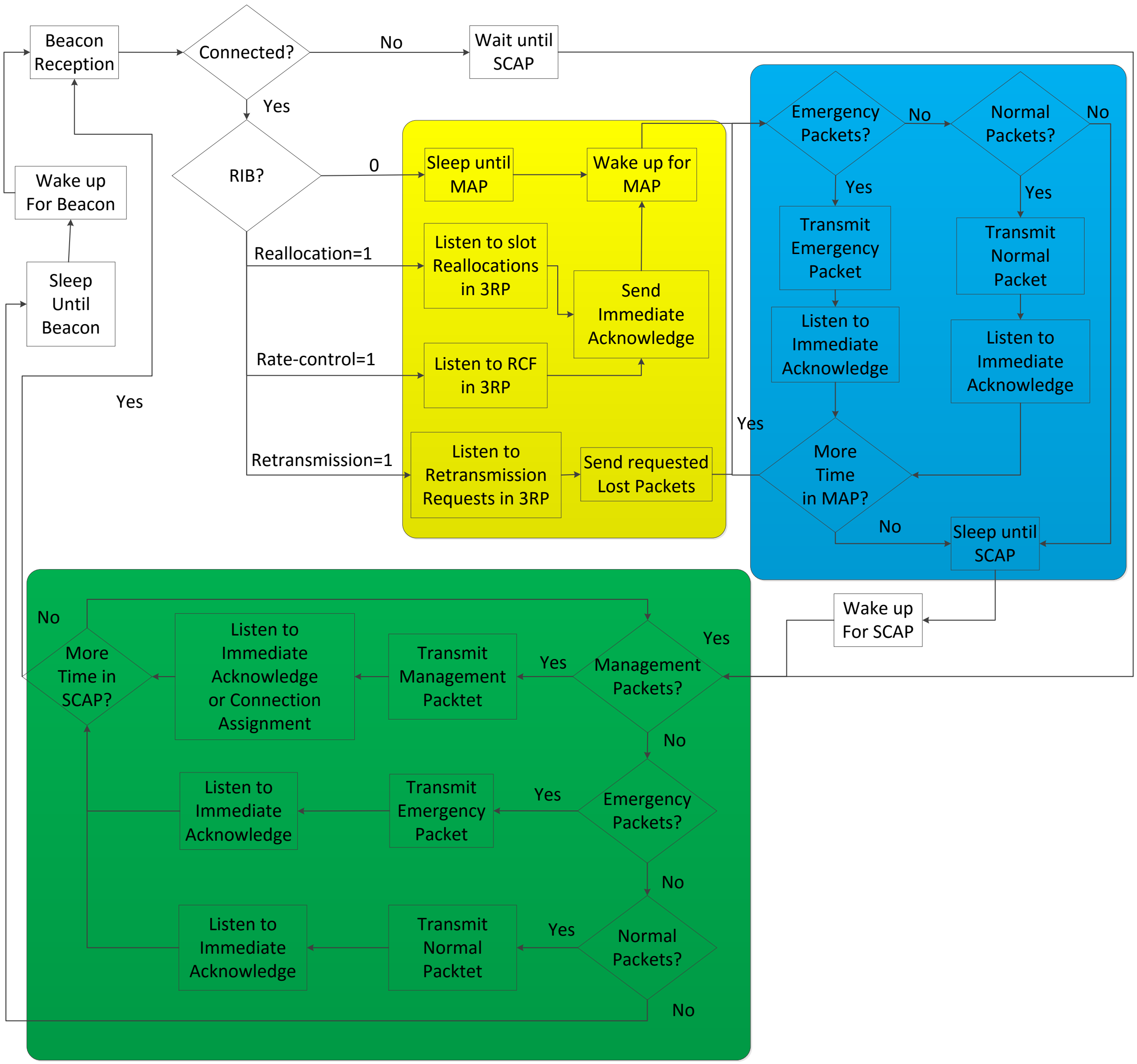

Figure 6.7. Behavior of the node for the proposed architecture

6.8 Architectures Comparison

The Table 6.3 presents a comparison of the proposed architecture with some architectures published recently and described in Chapter 2. In order to make the comparison with other architectures, we used the main requirements of all the architectures. The first architecture used for the comparison was a Context-Aware Service Architecture for the Integration of BSNs and

Social Networks through the IMS (Domingo, 2011). The second architecture was an Un-Obstructive BAN for Efficient Movement Monitoring (Felisberto et al., 2012). The third architecture was a Cloud-Enabled BAN for Pervasive Healthcare (J. Wan et al., 2013). The fourth architecture was a QoS-Aware Health Monitoring System using Cloud-Based WBANs (Almashaqbeh et al., 2014). The final architecture used for the comparison was a Configurable Energy-Efficient Compressed Sensing Architecture with its application on BSNs (A. Wang et al., 2016).

Table 6.3. Architectures Comparison

Requirement	**Proposed Architecture**	**Context-Aware Service Architecture**	**Un-Obstructive Architecture - Movement Monitoring**	**Cloud-Enabled Architecture - Pervasive Healthcare**	**QoS-Aware Health Monitoring System**	**Compressed Sensing Architecture**
Energy Efficiency	Yes	No	Yes	Yes	No	Yes
Reliability	Yes	No	No	Yes	No	No
QoS	Yes	No	No	Yes	Yes	No
Congestion Control	Yes	No	No	No	Yes	No
Rate Control	Yes	No	No	No	No	Yes
Loss Detection	Yes	No	No	No	Yes	No
Loss Recovery	Yes	No	No	No	No	No
Fairness	Yes	No	No	No	No	No
Emergency Awareness	Yes	Yes	Yes	Yes	No	No
Context Awareness	Yes	No	No	Yes	No	No
Security	No	No	No	Yes	No	No
Coexistence	No	No	No	No	Yes	No
Interference	No	No	No	No	Yes	No
Topology changes	No	No	Yes	No	No	No
Node Placement Optimization	No	No	Yes	No	No	No
Nodes Wearability	No	No	Yes	No	No	No
Energy Harvesting	No	No	Yes	No	No	No

6.9 Conclusions

The proposed architecture was explained in this chapter. Its assumptions, principles, topology, phases, protocols, schemes and requirements were enumerated and explained. The architecture is reliable, context-aware and energy-efficient and it is composed of: (i) an energy-efficient, context-aware and reliable MAC protocol; (ii) a reliable transport protocol based on loss-recovery and fairness; and (iii) a context-aware rate control scheme for congestion control in WBANs.

The main objective of this research project was accomplished with the design of a reliable, context-aware and energy-efficient architecture for WBANs, ensuring QoS and fairness in sports applications. The hub and the sensors are composed of five modules: (i) Sensing Module (SM); (ii) Memory Module (MM); (iii) Battery Module (BM); (iv) Processing Module (PM); and (v) Radio-Frequency Module (RFM).

The proposed architecture was compared with other architectures using the main requirements of all the proposed architectures. While some architectures focused on challenges like coexistence, interference, topology changes, node placement optimization, nodes wearability, and energy harvesting, the proposed architecture is the only one focused on energy efficiency, reliability, QoS, congestion control, rate control, loss detection, loss recovery, fairness, emergency awareness, and context awareness, all at the same time.

CHAPTER 7 CONCLUSION

7.1 Summary of the Thesis

There are many challenges posed for the design of WBANs. The most mentioned challenges are the Quality of Service, the energy efficiency, the nodes wearability, the context awareness, the reliability, the security, the variable network topology, the nodes placement optimization, and the coexistence and interference of WBANs in the vicinity. In this research project we have tackled four of the main challenges for WBANs: energy efficiency, Quality of Service, reliability and context awareness. We proposed a new reliable, context-aware and energy-efficient architecture for WBANs in sports applications composed of: (i) an energy-efficient, context-aware and reliable MAC protocol; (ii) a reliable transport protocol based on loss-recovery and fairness; and (iii) a context-aware rate control scheme for congestion control in WBANs.

The simulations of the protocols and schemes were made using OMNeT++ Simulator and Castalia Framework. The Castalia Framework provides a very good implementation of the IEEE 802.15.6 standard MAC protocol (called BaselineBAN) and the implementation of other MAC protocols like IEEE 802.15.4 standard MAC protocol, S-MAC (Sensor MAC), T-MAC (Timeout MAC) and a classical CSMA.

The main contributions of this research project include:

- First, we have proposed a new energy-efficient and emergency-aware MAC protocol for sports WBANs. The MAC protocol proposes two new phases into each beacon period: Slot Reallocation Phase (SRP) for slot reallocations and Management and Emergency Phase (MEP) for management traffic and additional emergency traffic. The simulation results have shown that the MAC protocol outperforms the IEEE 802.15.6 MAC protocol when the emergency probability is increased in each sensor node of the WBAN. This paper has been published in *the 2015 International Conference and Workshop on Computing and Communication (IEMCON)* (Jaramillo, Quintero, & Chamberland, 2015).
- Second, we have proposed SportsBAN a new energy-efficient, context-aware and reliable MAC protocol for Sports WBANs. SportsBAN proposes two new phases into each beacon period: Slot Reallocation Phase (SRP) for slot reallocations and Special Contention Access Phase (SCAP) for management traffic like connection requests, and

additional emergency and normal traffic. The simulation results have shown that the proposed MAC protocol outperforms the IEEE 802.15.6 MAC protocol, the IEEE 802.15.4 MAC protocol and the T-MAC protocol in the percentage of emergency and normal packet loss and latency. SportsBAN protocol also has a better energy-effectiveness than the three protocols for emergency and normal traffic. This paper is currently in evaluation in *Journal of Network and Computer Applications*.

- Third, we have proposed a new reliable transport protocol based on loss-recovery and fairness for Sports WBANs. The hub calculates the Fairness Index as the ratio between the number of lost packets and the total number of received packets in order to provide fairness between all the nodes in the WBAN. The simulation results have shown that the transport protocol outperforms the SportsBAN MAC protocol and the IEEE 802.15.6 Standard in the percentage of the packet loss with or without emergency traffic. The transport protocol also has a better energy-effectiveness than the other protocols with or without emergency traffic. This paper has been accepted to be presented in *Safe, Energy-Aware, & Reliable Connected Health (SEARCH 2016) in association with The First IEEE Conference on Connected Health: Applications, Systems and Engineering Technologies (CHASE 2016)*.
- Fourth, we have proposed a new context-aware rate control scheme for congestion control in WBANs. The hub calculates a Rate Control Factor (RCF) each time an emergency event happens in any node of the network. It sends the RCF to decrease the rate in nodes with normal traffic and to keep almost the same average rate in the whole WBAN. The simulation results have shown that the rate control scheme improved the performance of both the SportsBAN MAC protocol and the IEEE 802.15.6 standard. This paper is currently in evaluation in *the 12th IEEE International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob 2016)*.
- Finally, we have proposed a new reliable, context-aware and energy-efficient architecture for WBANs used in sports applications composed of the four works aforementioned. The architecture proposes three phases for each beacon period: 3RP (Reallocation, Retransmission & Rate-control Phase) – used by the hub for sending slot reallocations, retransmission requests and the Rate Control Factor (RCF) to all nodes. MAP (Managed

Access Phase) – used by all nodes for sending normal an emergency traffic, always giving the highest priority to the emergency traffic. SCAP (Special Contention Access Phase) – used by all nodes for sending connection requests and additional normal and emergency traffic. The architecture proposes the use of three extra bits within each beacon for indicating whether the hub is going to assign slot Reallocations, to request for lost packet Retransmissions, to send Rate-control requests, or any combination of them. The hub and the sensors are composed of five modules: (i) Sensing Module (SM); (ii) Memory Module (MM); (iii) Battery Module (BM); (iv) Processing Module (PM); and (v) Radio-Frequency Module (RFM).

7.2 Limitations

This research project with all the proposed protocols and schemes are conditioned by some limitations like:

- The proposed architecture tackles only four of the main challenges to design WBANs: Quality of Service, reliability, energy efficiency and context awareness. This work does not address other important challenges presented in the design of WBANs like security, coexistence and interference, topology changes, node placement optimization, nodes wearability, and new energy harvesting sources.
- The Slot Reallocation Technique used by the MAC protocol “SportsBAN” proposed in Chapter 3 does not consider some additional parameters from the nodes like the priority, the packet rate, the sampling frequency, the total number of lost packets and the total number of received packets.
- The proposed architecture does not consider the coexistence and interference of WBANs in the vicinity. The interference with other WBANs cannot be avoided, but it can be mitigated with the implementation of some mechanisms like the beacon shifting, the channel hoping and the active superframe interleaving as the IEEE 802.15.6 standard suggests.
- The proposed architecture is focused only in sports WBANs, but it could be extended to medical WBANs. The emergency and context awareness and the reliability offered by the proposed architecture could also be useful for medical WBANs.

- The validation of each protocol and scheme was made through simulations in OMNeT++ and the validation of the whole architecture was made through the comparison with other architectures. The validations could be improved with a testbed.

7.3 Future Work

The future research will be focused mostly in tackling the limitations aforementioned. This future work includes:

- Improvement of both the Slot Reallocation Technique of the MAC protocol proposed in Chapter 3, and the Rate Control Scheme proposed in Chapter 5. This improvement will consider more specific parameters from the nodes like the priority, the packet rate, the sampling frequency, the total number of lost packets, the total number of received packets, the battery level, and the buffer (management, emergency and normal) level. This improvement must be made through the balance between the power consumption and the desired reliability of the WBAN.
- Working in other important challenges to design WBANs like high-security mechanisms and topology changes support. With the consideration of security, the solution could be more likely to be used by sportsmen.
- Improvement of the MAC protocol proposed in Chapter 3 for considering coexistence and interference of WBANs in the vicinity. This improvement could be achieved by the inclusion of mechanisms like the beacon shifting, the channel hoping and the active superframe interleaving proposed in the IEEE 802.15.6 standard.
- Development of new energy-efficient routing protocols taking advantage of the coexistence of other WBANs in the vicinity. This kind of protocol could be used in team sports like soccer, basketball, baseball and all kinds of team sports played over a field. The information can be transmitted from the WBAN source through all the WBANs worn by the team mates until reaching the coordinator device managed by the coach, and then, it can be sent to other stakeholders.
- Using of an accurate mobility model to capture the behavior of human bodies in order to support topology changes and fading channels.

- Development of new cross-layer architectures including the application, network and physical layers. This kind of architecture could help to improve the energy consumption, the Quality of Service and the reliability of the whole WBAN.
- This work could be extended to help to improve skills, performance, endurance and training protocols of athletes, and deficiency detection. It could also be extended to enhance the quality of life of children, ill and elderly people, and even to security, military and entertainment fields.

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